Bulgarian Soil Science Society

BULGARIAN JOURNAL OF SOIL SCIENCE®

2026 Volume 11 Issue 1 e-ISSN: 2367-9212 ISSN: 2534-8787

BULGARIAN JOURNAL OF SOIL SCIENCE®

Peer Reviewed Open Access Journal

Published by Bulgarian Soil Science Society

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Short-Term Chemical Changes in Sandy Soil Following Composted Solid Winery Waste Application and NPK Fertilisation under Swiss Chard Cultivation

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Received: 15 November 2025 *Accepted: 01 February 2026*

Abstract

Soil fertility challenges, particularly for smallholder farmers, are often addressed with inorganic fertilisers, which can lead to soil degradation. This study investigates a sustainable alternative by comparing the short-term effects of NPK fertilisation and two different application rates of composted solid winery waste on sandy soil cultivated with Swiss chard. The study used a randomised complete block design with four treatments (control, NPK, low-rate composted solid winery waste, and high-rate composted solid winery waste). Soil samples were taken at bi-weekly intervals over eight weeks (4 intervals) to assess chemical properties, including pH, phosphorus (P), potassium (K), and various exchangeable cations. The results showed that the NPK fertiliser provided a rapid but temporary increase in nutrients, and it also caused significant soil acidification and a decline in P availability. In contrast, the high-rate composted solid winery waste application effectively ameliorated soil pH ($p<0.05$) and provided a more gradual and sustained release of nutrients, particularly P and K, throughout the observation period. The low-rate composted solid winery waste was found to be insufficient to produce significant chemical changes. These findings demonstrate that utilising composted solid winery waste as a soil amendment, in the short term, is a more environmentally friendly approach than relying on inorganic fertilisers. This aligns with the principles of a circular economy and turns a waste product into a valuable resource for improving soil health and fertility.

Keywords: inorganic fertiliser, solid winery waste, Swiss chard, soil chemical properties, circular economy.

Introduction

Soil fertility is a leading production challenge faced by many smallholder farmers in Africa (Vanalauwe and Giller, 2006). Soil fertility declines have been linked to inappropriate land use, such as monocropping, inadequate fertiliser use, and complete removal of crop residues (Aleminew and Alemayehu, 2020). Soil fertility declines lead to reduced crop yields, which is challenging given the need to feed the ever-growing human population in Africa (Raimi et al., 2017; Chaudhary et al., 2023). In recent years, soil fertility declines have largely been ameliorated using inorganic fertilisers (Sindesi et al., 2023). Over-reliance on inorganic fertilisers can cause soil degradation, including reduced organic matter and soil acidification, which leads to decreased fertility and plant health (Kopittke et al., 2019). In response to these challenges, the global movement towards a circular economy advocates for systems where materials are never treated as waste, and natural processes are regenerated (De Sa and Korinek, 2021). This approach encourages the sustainable and environmentally friendly use of organic by-products from various industries.

The wine industry produces various types of winery waste, including solid and liquid wastewater. This winery waste is normally discarded into the fields or burned, thus causing environmental problems (Genisheva et al., 2023). Liquid winery waste poses a direct threat to aquatic life through oxygen depletion and water pollution from its high organic content, low pH, and salinity (Ioannou et al., 2015). Solid winery waste has phytotoxicity due to high levels of organic acids and phenols. Furthermore, solid winery waste that is not properly treated could pollute the soil, air and water (Zingela, 2006). Composting solid winery waste for crop cultivation is an alternative to landfill and burning for waste disposal (Bertran et al., 2004). The application of compost increases the percentages of organic matter, nutrient levels (providing a slow fertilisation action over a long period of time), microbial biomass and improves the soils' physical properties (aeration, water holding capacity, etc.) (Bertran et al., 2004). While the use of compost is known to improve soil health, there is limited research directly comparing the specific chemical changes in a single soil type of soils fertilised with NPK fertiliser versus different composted solid winery waste, especially under the cultivation of a specific crop such as Swiss chard. This study evaluates and compares the short-term effects of NPK fertilisation and two different rates of composted solid winery waste on the chemical properties of sandy soil under Swiss chard cultivation.

Materials and Methods

Experimental site:

A field experiment was conducted at the Agricultural Research Council (ARC), Bien Donné Farm, Paarl, Western Cape, South Africa (33.84274°S and 18.98425° E). The study investigated the effects of composted solid winery waste and inorganic fertiliser (NPK) on the chemical characteristics of sandy soil cultivated with Swiss chard. Swiss chard was cultivated for 8 weeks (April to June). Paarl is characterised by a Mediterranean climate, with cool, rainy (approximately 450-500mm annually) winters and hot, dry summers (Harebottle et al., 2008). Most of the rain falls between May and October. Winter temperatures can drop to a

minimum of 10°C, while summer temperatures can go up to 35°C. The climate in this region is ideal for agricultural production and supports the region's wine and fruit production.

Composted Solid Winery Waste Production

The composted solid winery waste was produced using the method described in the study by Masowa et al. (2016). By co-composting filter materials (FMs), consisting of perlite and diatomaceous earth obtained from winery waste, with grape marc and chopped grapevine pruning canes used as bulking material (BM). FMs were mixed with the BMs at 40% FM and 60% BM. The composting was done in a static heap, with a heap measuring 2 x 1.5 x 1 m (L x W x H) over 13 weeks under aerobic-thermophilic conditions without turning. Additionally, temperature was maintained at 38.3 °C during the composting period, and compost was maintained at 50 to 60% moisture content.

Experimental design:

The study was arranged in a randomised complete block design (RCBD) with four treatments replicated four times. Each replicate was assigned to a 4 m * 4 m sub-plot, and the total experimental field was 256 m². The control treatment had no compost and no inorganic fertiliser application. T1 was applied with inorganic 2:3:4 (30) - 5g Zn% fertilisers (500 kg ha^{-1}) before planting and 175 kg ha^{-1} LAN (28) at 4 and 8 weeks after planting. T2 was applied with 2.18 t ha^{-1} of composted solid winery waste, while T3 was applied with 8.72 t ha^{-1} of composted solid winery waste. The chemical composition of the used winery waste is shown in the Table. 1 below. The chemical composition of the composted solid winery waste used in this study presented two primary concerns: high alkalinity (pH 10.3) and a high sodium (Na) concentration (10525.50 mg kg^{-1}).

Table 1. *Chemical composition of the composted solid winery waste*

Characteristic	Unit	Value
Total Organic Carbon (C)	%	11.9
Total Nitrogen (N)	%	1.23
C/N Ratio	–	10
Na	mg kg^{-1}	10525.5
Ca	%	0.75
Mg	%	0.15
K	%	6.57
P	%	0.48
pH (KCl)	–	10.3

Agronomic practices:

Before planting, the field was tilled using a disc plough, followed by a disk harrow 4 weeks before seedling transplanting to achieve fine tilth. Composted solid winery waste was also applied 1 week before seedling transplanting. Healthy vigorous six-week-old Swiss chard seedlings were transplanted at a spacing of 50 cm between plants and 70 cm between rows. Tension-meters were installed at soil depth 0-30 cm in each block to monitor soil moisture for irrigation scheduling. Irrigation was applied using micro-jets (1.5 L hr^{-1}), and irrigation was done three times a week. Weeds were controlled using a hand spade when needed, insect pests were controlled using a registered insecticide, alpha-cypermethrin (pyrethroid) 100 g L^{-1}

(ALPHA-THRIN 100 SC ©) mixed with 3 ml ALPHA, 10 ml liquid detergent and 25 L of water.

Data Collection:

Soil chemical composition: A composite soil sample was taken using a soil auger at soil depth 0-30 cm before seedling transplanting. Representative samples, three from each subplot, were taken 2, 4, 6 and 8 weeks after transplanting. The soil was analysed for phosphorus (P), potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), and soil pH. Soil nitrogen (N) was not analysed after the application of treatments. The analysis methods used were the ICP-OES method for K, and the Bray II method for P. Soil exchangeable Ca, Mg, and Na were extracted using 1.0 N ammonium (NH_4^+) acetate. While soil pH was measured using the 1.0 N KCl method (Non-affiliated Soil Analysis Work Committee, 1990). The baseline soil chemical characteristics for the soil are presented in Table 2.

Table 2. Baseline soil properties

Parameter	Unit	Value
Soil Depth (cm)	cm	0–30
pH (KCl)		6.00
P (Bray II)	(mg kg^{-1})	25.30
K	(mg kg^{-1})	54.00
Na	(cmol (+) kg^{-1})	0.06
Ca	(cmol (+) kg^{-1})	3.92
Mg	(cmol (+) kg^{-1})	0.88

Data analysis

Data were subjected to an analysis of variance (ANOVA) using SAS (version 9.4, SAS Institute Inc., Cary, NC, USA, 2000). Treatment means were separated using Fisher's least significant difference (post-hoc test), and the difference was calculated at the 5% level. A probability level of 5% was considered significant for all tests of significance.

Results and Discussion

Soil pH response to composted solid winery waste and NPK fertilisation

Soil pH is the most important factor for crop growth in agriculture, as it influences the availability of nutrients to plants (Dewangan et al., 2023). Soil pH is influenced by a variety of factors, such as inherent factors, which include parent material, climate and soil texture. These inherent factors provide the soil with its initial chemical characteristics. Other factors which influence soil pH in agriculture are organic matter inputs, production practices such as the use of N-based fertilisers, cropping systems, and tillage practices (Oshunsanya, 2018). The application of nitrogenous fertilisers has been observed to increase soil acidity (Sharma et al., 2022). Organic compost applications have been linked to reduced soil acidity (Hassin et al., 2022). Organic composts also act as a pH buffer, helping to stabilise soil pH rather than causing drastic changes (Dvořáčková et al., 2022). The sandy soil used for this study was slightly acidic, with a pH of 6; however, it was still within the optimal range for Swiss chard growth. In week 2, all the treatment soils showed reductions in soil pH, with the control, T2

and T3 showing less reduction than T1. This may be attributed to tillage or irrigation practices used on the soil to prepare it for transplanting.

The pH of soils which were applied with NPK fertiliser and later with LAN (T1) reduced ($p<0.05$), becoming more acidic, from the initial soil pH (Fig. 1). The acidification of the soils by the second week can be linked to the N component in the NPK fertiliser used. NPK fertilisers contain N in the form of NH_4^+ or compounds that convert to NH_4^+ in the soil, such as urea. The process that causes the decrease in pH is called nitrification, as the process produces protons (H^+), which increase the acidity (Grzyb et al., 2021; Mshweshwe et al., 2025; Sindesi et al., 2025a). Treatments 2 and 3 only showed significant pH changes in week 4, where T3 showed superior soil pH amelioration than the rest of the treatments. The application of composted solid winery waste increased soil pH by adding alkaline materials, such as K (Ho et al., 2022). The composted solid winery waste used had high K (6.57%) content along with an alkaline nature (pH 10.3). These results support earlier findings (Bustamente et al., 2008; Novoa-Munoz et al., 2008), in which acidic soil was rectified over time utilising compost from winery waste sources on a few crop species. This effect is not clearly seen on T2 and can be attributed to the amount of compost applied. T3 had about four (4) times the amount of compost applied on T2. It is possible that the amount of compost applied to T2 was insufficient for a drastic pH change.

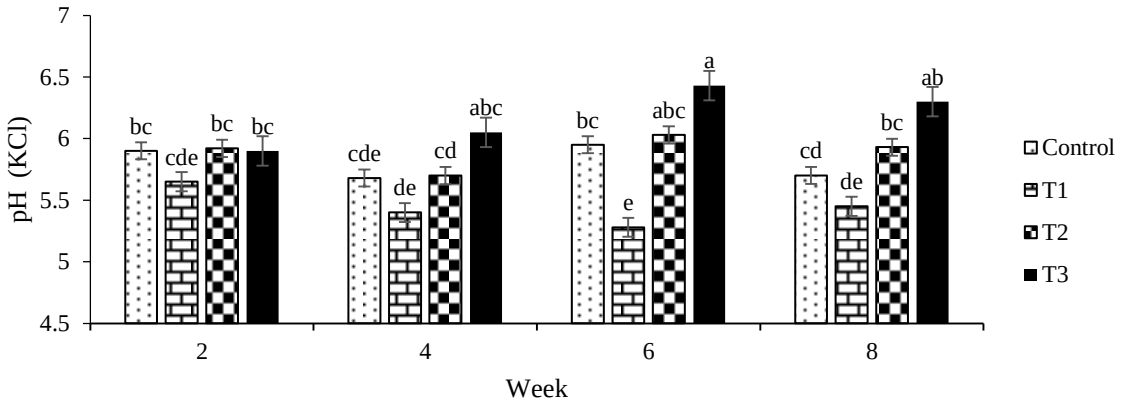

Figure 1. *Soil pH (KCl) responses to composted solid winery waste and NPK fertilisation. Bars with the same letter show no significance at p<0.05*

Effect of composted solid winery waste and NPK fertilisation on soil P

P is a crop-limiting nutrient; it is inefficiently used by plants due to soil immobilisation and fixation, which result in low bioavailability (Mardamootoo et al., 2021). In plants, P stimulates root development, as a result, it facilitates improved moisture and nutrient uptake (Mashece et al., 2025). Soil P availability is influenced by several factors such as soil pH, temperature, salinity, and organic matter content (Xie et al., 2022). Among these, the application of NPK fertilisers, apart from directly increasing soil P, also influences soil pH, while the application of composted solid winery waste influences both soil pH and organic matter content. Figure 2 illustrates the results of the influence of composted solid winery waste and NPK fertiliser on soil P. In week 2, the NPK treatment showed higher ($p<0.05$) levels of soil P than the other treatments. This is because NPK provides plant-available P, spiking the availability of soil P for a short time. When P-based fertilisers are applied, a portion of the P is in its soluble form ($Ca(H_2PO_4)_2$). This allows for an immediate

increase in the concentration of plant-available P in soils (Schipanski, 2021). The spike in availability is a direct result of the chemical composition of the used fertiliser, making the nutrient readily accessible for plant uptake. By the fourth week, T2 observed a drastic decrease ($p<0.05$) in plant-available P, which was maintained until the eighth week. The decrease may be due to P fixation and immobilisation within the soil (Li et al., 2023; Chatterjee et al., 2014). In fixation, P ions react with other minerals in the soil, such as Ca in alkaline soils, or iron (Fe) and aluminium (Al) in acidic soils (Li et al., 2023). In immobilisation, soluble P is taken up by soil microbes to support their own growth, therefore, incorporating P into their biomass, making it temporarily unavailable to plants (Chatterjee et al., 2014). The former is considered the main cause of the T2 observed P trend, as the soil pH during this time was acidic. This is further confirmed by the optimal soil pH range for P bioavailability, being very slightly acidic (6.5) to moderate alkalinity, 8.0 (Potash Development Association, 2005)

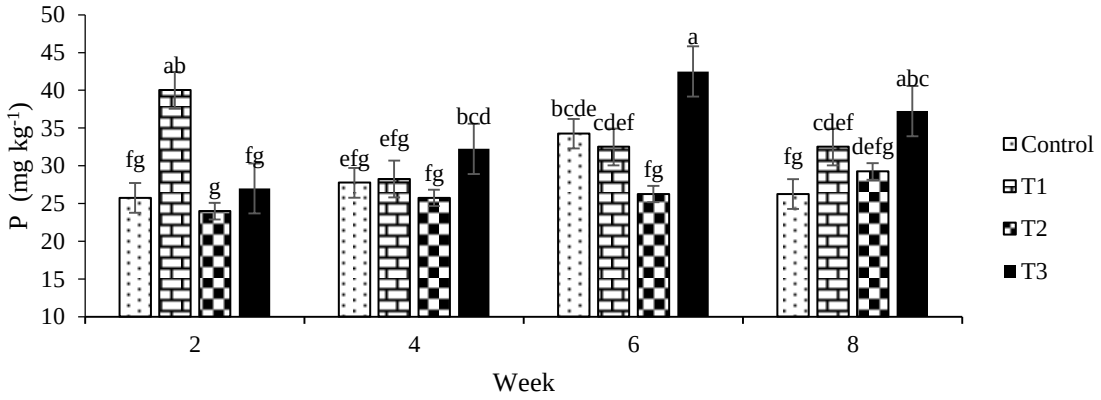

Figure 2. *Effect of composted solid winery waste and NPK fertiliser on soil phosphorus (mg kg^{-1}). Bars with the same letter show no significance at $p<0.05$*

T3 showed a gradual increase ($p<0.05$) in soil P from the second week to the sixth week, with a slight decrease in week 8 ($p>0.05$). Also, T2, apart from showing less P in week 2 and week 4 than the control, it slightly increased ($p>0.05$) plant-available P throughout the weeks. The trends indicate a slow release of P by composted solid winery waste; hence, the composted solid winery waste had 0.48% P content. Additionally, the slight decrease in plant-available P in week 8 is likely due to a combination of plant uptake, microbial activity, and P fixation as the compost breaks down. As the plant grows, P requirements increase to support the energy-intensive processes of cell division and structural development in newly formed tissues (Malhotra et al., 2018). P fixation and immobilisation may also explain the decrease, as the newly released inorganic P is still subject to the same soil fixation processes as synthetic fertilisers. As micro-organisms reach peak activity and continue to proliferate, they assimilate available soil P to support their growth (Montreemuk et al., 2024)

Effect of composted solid winery waste soil application and NPK fertilisation on soil K

K plays an important role in plant growth and metabolism, including enzyme activation, protein synthesis, stomatal regulation and ion absorption (Prajapati and Modi,

2012). K availability in soil is influenced by numerous factors, including soil chemistry, physical properties, biological factors, and management practices (Mouhamad, 2016). In this study, soil K increased with time for all the treatments; only T2 and T3 showed a significant increase (Table 2). This may be due to accelerated mineral weathering, which is influenced by tillage (Liu et al., 2021). Additionally, the slightly higher ($p>0.05$) amounts of K in the NPK amended treatments than the control can be attributed to the available K within the NPK fertiliser. Furthermore, the increased application of composted solid winery waste containing 6.57 % K also increased soil K. Hence, the values of soil K 8 weeks after transplanting the seedlings are almost four times greater on T3 than on T2. This is partially because T2 received four times less composted solid winery waste than T3. This increase ($p<0.05$) in K in the compost treatments could also potentially be attributed to increased microbial activity brought on by the addition of organic wastes, which could hasten K cycling. Additionally, these findings are consistent with the findings of Bustamente et al. (2008), which indicated that high soil K concentrations could be linked to a high proportion of winery and distillery waste products with high K concentrations.

Table 3. *Influence of composted solid winery waste and NPK fertiliser on soil K (mg kg^{-1}).*

Week	2	4	6	8
Control	51.25^{g}	53.50^{g}	53.75^{g}	56.25^{fg}
T1	79.75^{efg}	68.00^{fg}	61.50^{fg}	63.00^{fg}
T2	64.00^{fg}	87.50^{ef}	140.25^{d}	142.00^{d}
T3	111.75^{de}	321.50^{c}	362.0^{b}	414.75^{a}

Note: Means in the same column with different superscripts are significantly different from each other ($P<0.05$)

Soil exchangeable cations response to composted solid winery waste and NPK fertilisation

The exchangeability of cations in the soil is governed by the cation exchange capacity (CEC) as well as soil pH (Sindesi et al., 2022). Exchangeable Ca was reduced from the initial soil exchangeable Ca of 3.92 cmol (+) kg^{-1} for all treatments. The consistent decrease across all treatments is primarily attributed to the high Ca demand observed in Swiss chard during its active growth phase (Pokluda and Kuben, 2002; Mzoughi et al., 2019). There were no significant ($p>0.05$) changes in exchangeable Ca across treatments (Fig. 3) nor with passing time, although T2 showed slightly better ($p>0.05$) exchangeable Ca from week 4 onwards. This is because the used NPK fertiliser did not contain any Ca. Additionally, the lack of response to the composted treatments is directly linked to the compost composition. The composted solid winery waste had almost negligible Ca of 0.75%. This value is significantly lower than the 1.5-3.5% range required for high-quality compost directed towards improving soil mineral status (Sultanaa et al., 2022). Consequently, the compost application failed to supply sufficient Ca to counteract the continuous Swiss chard uptake. It could not meet the Swiss chard Ca demand and replenish the soil's exchangeable pool. Therefore, treatment and time did not influence the availability of Ca.

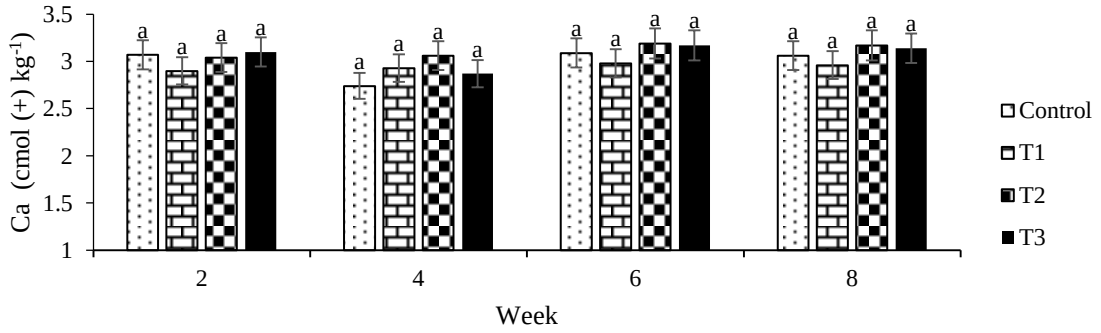

Figure 3. *Responses of Ca (cmol (+) kg^{-1}) to composted solid winery waste and NPK fertilisation. Bars with the same letter show no significance at p<0.05*

Regardless, T3, with the highest composted solid winery waste, had the highest (p<0.05) exchangeable Na (Fig. 4) among the treatments throughout the observation weeks. The used composted solid winery waste had high levels of Na (10525.50 mg kg^{-1}). Furthermore, exchangeable Na remained constant on this treatment, while for the other treatments, there were slight fluctuations, particularly in the control. The fluctuations may be caused by a variety of factors, such as leaching, plant uptake and salt accumulation after moisture evaporation (Tarolli et al., 2024). Soil exchangeable Mg also decreased from the initial soil Mg (Fig. 5). This observed decrease is linked to plant uptake, while the lack of significant treatment effect is associated with the limited Mg in the applied compost. The composted solid winery waste contained only 0.15% Mg. This level was less than the standard range required for compost intended for field application, a range of 0.25 to 0.7% as noted in the work by Sullivan et al. (2018). As a result, even the high compost application (T3) rate failed to provide enough Mg to mitigate the nutrients removed by Swiss chard. Overall, exchangeable Mg did not show any significant differences across treatment and across time. However, a slightly higher (p>0.05) Mg value was observed on the control treatment in week 6. The non-significant findings suggest that over the short term, the inherent characteristics of the sandy soil were the main drivers of exchangeable Mg behaviour. Specifically, the low CEC and natural buffering mechanisms offset the effect of the low-nutrient-content amendments. Nevertheless, these results contradict earlier findings by Dikinya et al. (2010), who found increased Mg with increasing rates of composted chicken manure.

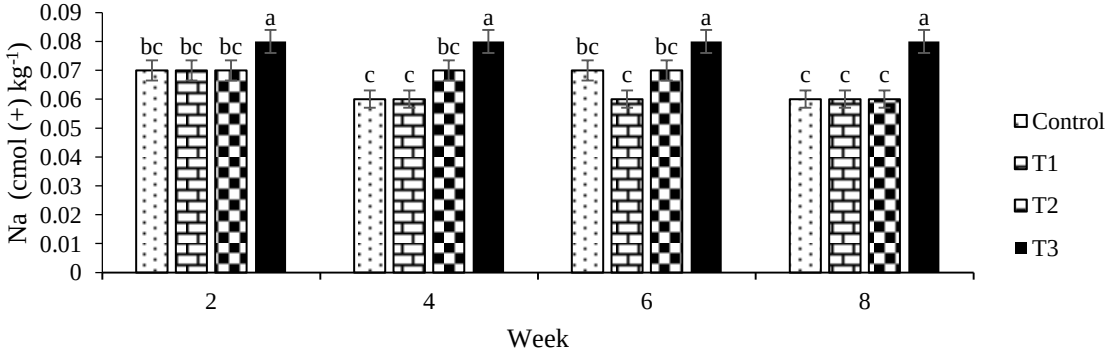

Figure 4. *Effect of winery waste and NPK fertilisation on soil exchangeable Na (cmol (+) kg^{-1}). Bars with the same letter show no significance at p<0.05*

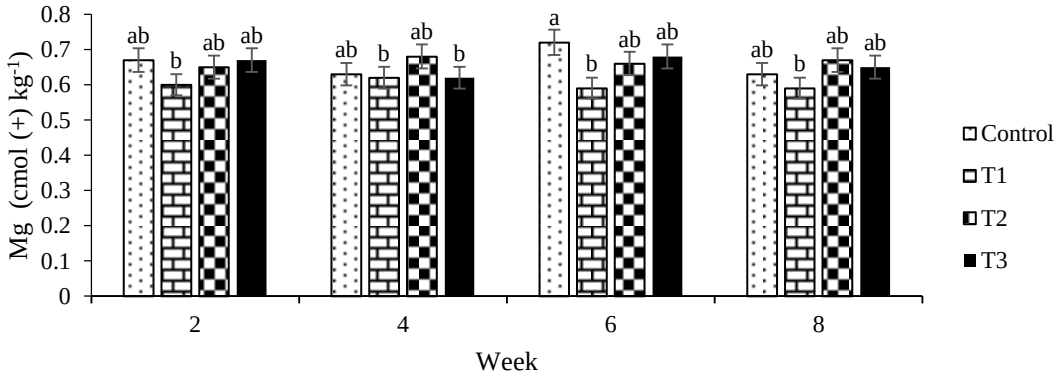

Figure 5. *Responses of soil exchangeable Mg (cmol (+) kg^{-1}) to composted solid winery waste application and NPK fertilisation. Bars with the same letter show no significance at p<0.05*

Implications and limitations regarding N dynamics

A key aspect of this study was to compare the effect of NPK fertilisation with composted solid winery waste. As such, N dynamics are a major driver of the observed soil chemistry and Swiss chard response. However, a critical limitation of the current study is the omission of soil N, which is essential for evaluating the availability of N over time. Nevertheless, the role of N on pH has been inferred based on the pH results. The process of nitrification, which converts the NH_4-based N sources into nitrate, releases hydrogen ions (H^+) or protons, thereby increasing soil acidity and reducing soil pH (Mshweshwe et al., 2025; Sindesi et al., 2025a). While the high-rate compost treatment (T3), despite having a low C: N ratio of 10, had a highly alkaline pH of 10.3. This high alkalinity may have exceeded any potential acidifying effects from N mineralisation, resulting in pH amelioration. N is the primary component of protein and nucleic acids in plants (Sindesi et al., 2025b). It plays a crucial role in regulating meristematic cell activity and promoting cell division (Sindesi et al., 2025a). The contrasting N supply, rapidly available inorganic N from the NPK treatment versus slow-release organic N from the compost, was expected to create differing growth patterns. This expectation is consistent with the findings reported by Mungoche et al. (2023). The dynamic growth expected from the NPK treatment was observed only on one Swiss chard growth parameter, the number of leaves per plant, at week 2 (Ndololwana et al., 2026). This observation is linked to the availability of N applied before the transplanting of seedlings. Nevertheless, after week 2, this observation disappeared, suggesting a potential leaching of N or reduced N efficiency linked to reduced soil moisture. This is consistent with the suggestion by Wang et al. (2025) that when soil moisture is in a restricted state, excessive application of N fertiliser not only fails to promote plant growth but also produces antagonistic effects. Soil moisture may easily evaporate in soils with reduced or minimal levels of organic matter (Zhang et al., 2021).

Conclusion

This study assessed the short-term effects of inorganic NPK fertiliser and two application rates of composted solid winery waste on the chemical properties of a sandy soil under Swiss chard production. The findings provide valuable initial insight into the immediate

chemical responses of sandy soil to composted winery waste; however, several limitations are acknowledged. Firstly, the experimental duration of 8 weeks captures only short-term changes and does not reflect long-term soil responses or the eventual fate of the high Na introduced by the compost. Secondly, the trial was conducted on a single sandy soil type; therefore, results cannot be generalised to soils with different textures or chemical characteristics. Lastly, this study focused on soil chemistry only; the absence of soil N and C data following compost application, as well as the lack of crop yield measurements, limits the ability to link observed chemical improvements to agronomic performance. Additionally, worth noting, the chemical composition of the composted solid winery waste presented two key concerns: high alkalinity (pH 10.3) and critically elevated Na content (10525.50 mg kg^{-1}). While the high pH, driven by basic cations such as K, effectively corrected the initial soil acidity, the immediate benefit is offset by the increased exchangeable Na, which poses a severe potential long-term salinity and sodicity hazard. This increased exchangeable Na warrants further investigation to determine whether these benefits persist and, most importantly, to evaluate the eventual fate and potential toxicity risks associated with the high Na loading over multiple cropping seasons. Despite these constraints, clear trends emerged. NPK fertiliser delivered an immediate but short-lived nutrient boost and contributed to soil acidification and reduced P availability over time, likely due to fixation and microbial immobilisation. In contrast, the high-rate compost treatment produced the most comprehensive improvements, including pH amelioration and a sustained release of nutrients, especially P and K, throughout the study period. The lower compost rate produced minimal chemical change across most soil parameters. This observation suggests that the minimum threshold application rate of compost necessary to produce a significant soil chemistry change was not met. This further emphasises the importance of adequate application levels for organic amendments in nutrient-poor sandy soils. Overall, the results demonstrate that composted solid winery waste, particularly at higher application rates, offers a more sustainable soil-amendment option than inorganic NPK fertiliser. Its use contributes to the circular economy by transforming an agricultural waste product into a valuable soil-conditioning resource. Long-term studies are needed to determine whether these benefits persist over multiple cropping seasons, as well as to evaluate effects across a broader range of soil types and crops. Finally, future work should aim to identify an optimal, cost-effective application rate suitable for smallholder farmers, given that the low rate tested here was insufficient to drive meaningful soil chemical improvement. In line with this, future studies must include the change in key agronomic parameters, such as crop biomass and plant physiological observations. These performance indicators are necessary for a holistic assessment of the agronomic implications of the observed soil chemical improvements.

Funding: *The authors would like to express their gratitude to the University Research Fund (URF) of Cape Peninsula University of Technology and the ARC-Stellenbosch station for financial support.*

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Sustainable Technology for Establishment and Management of a Field-Protective Forest Belt with Accompanying Agricultural Crops and Soil Microbiological Assesment in the State Forestry Enterprise "Dobrich", Northeastern Bulgaria

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Received: 27 December 2025 Accepted: 01 February 2026

Abstract

The establishment and sustainable management of field-protective forest belts represent a key component of ecological infrastructure in agricultural landscapes. This study aims to develop a sustainable technological scheme for the establishment and management of a field-protective forest belt combined with accompanying agricultural crops in the area of the Dobrich State Forest Enterprise, Northeastern Bulgaria, integrating soil microbiological indicators as an assessment tool for ecological functionality.

The proposed technology is based on site-specific environmental conditions and prioritizes Turkey oak (*Quercus cerris* L.) as the main forest species due to its high drought tolerance, wind resistance and long-term vitality under the conditions of Dobrudzha. Watermelon (*Citrullus lanatus* (Thunb.) Matsum. & Nakai) and sweet cherry (*Prunus avium* L.) are selected as accompanying agricultural crops within an agroforestry framework, providing ecological and economic benefits. The technological plan includes mechanized soil preparation and planting, followed by a five-year tending period combining mechanized and manual operations.

Soil microbiological analyses conducted in spring under *Quercus cerris* (L.), *Citrullus lanatus* (Thunb.) Matsum. & Nakai and *Prunus avium* (L.) revealed a higher relative abundance of non-spore-forming bacteria, actinomycetes and filamentous fungi in forest soils, while agricultural soils were dominated by spore-forming bacteria. The results indicate that integrating field-protective forest belts with agricultural crops will enhance soil biogenicity, stabilize agrolandscapes and supports sustainable land management. Continuous monitoring of soil microbiological indicators is recommended to assess long-term ecological sustainability.

Keywords: forest belt; agroforestry systems; *Quercus cerris*; soil microorganisms; Dobrudzha region

Introduction

A fundamental prerequisite for establishing shelterbelts is their ability to exert a beneficial influence on wind erosion, the soil water regime, the even distribution of snow cover, and the increase in crop yields from adjacent lands. These are linear forest plantations whose creation is particularly essential in regions with prolonged summer droughts and destructive northern, northwestern, and northeastern winds, such as Northern Bulgaria and, more specifically, the Dobruja region. The greatest protective effect is achieved when the belts are interconnected in a network, forming inter-belt cells.

The full development of agriculture, forestry, and other economic sectors that rely on natural resources is linked to the intensification of production and the use of various chemical fertilizers, biostimulators, and other inputs. Alongside their positive effect - namely, increased productivity - these inputs disrupt natural cycles of matter and energy turnover. They negatively affect the morphological structure of the environment and its ability to maintain its natural qualities and to regenerate exploited resources. Consequently, the capacity for continued existence and sufficient regeneration of vegetation and fauna is substantially diminished due to constantly changing natural conditions (Peev, 1989).

Shelterbelts are an integral part of the ecological infrastructure of agricultural landscapes in Bulgaria. They perform essential functions in protecting against wind erosion, retaining soil moisture, improving the microclimate, increasing agricultural crop yields, and creating resilient ecosystems. In the Dobruja region, their significance is particularly high due to the predominantly flat terrain, intensive agriculture, and frequent occurrences of drought and wind erosion. This calls for the development of technological solutions for the establishment and cultivation of shelterbelts under conditions of climate change and intensive land use. In their study of shelterbelts in Northeastern Bulgaria, Dodev et al. (2023a) report that Turkey oak and Sessile oak demonstrate resilience, while mass dieback has been observed in ash belts, and phased reconstruction is deemed necessary for belts of black locust, green ash, and field elm. The effectiveness of shelterbelts in Dobruja is considerable, and thanks to them farmers report higher yields. Shelterbelts and agricultural lands together form an agroforestry system and represent biodiversity oases within the otherwise uniform landscape of Dobruja.

Sustainable land management, including the stabilization of landslides and erosion processes, requires a combination of engineering and biotechnical methods that minimize environmental impacts. Biotechnical approaches rely on vegetation that improves the soil water regime and enhances soil stability. Mountainous and erosion-prone terrains must be viewed as integrated systems in which vegetation plays a key stabilizing role. When establishing shelterbelts, vegetation not only protects against wind erosion but also stabilizes soil structure and microclimatic conditions. Landslides in the Varna region remain a significant problem that requires continuous attention, funding, and complex engineering solutions to ensure public and infrastructural safety (Tsekova, 2025a). Recommendations for strengthening slope stability must be followed, both for Varna landslides and for the "Smolyan Lakes" landslide (Tsekova & Trizlova, 2025). All interventions in the land base or landscape must be evaluated for the risk of secondary negative processes such as erosion, landslides, and disruption of the water balance. The construction of shelterbelts must also be assessed with regard to fire risk in the area. Human activities such as deforestation and land-

use change for agriculture and urban development not only cause ignition events but also alter landscape susceptibility to wildfire, creating a dangerous feedback loop (Tsekova, 2025b). Therefore, the establishment of shelterbelts requires ecological assessment and careful spatial planning in the selection of species and belt locations.

The ecological approach to construction and landscape modeling requires minimal disturbance of natural ecosystem linkages. This principle is equally applicable to combining agricultural crops with protective forest plantations, where ecological compatibility is a leading criterion. Any intervention in the natural environment must be evaluated in advance in terms of ecological compatibility and potential risks. For example, wind farms can alter the landscape and be perceived as visual pollution; their construction may also lead to soil erosion and water contamination (Trizlova et al., 2025). This approach is highly relevant for shelterbelt design, particularly when integrating them with agricultural crops, where achieving a balance between ecological sustainability and economic efficiency is crucial. As the authors emphasize, environmental protection should remain a fundamental principle in all infrastructural and eco-engineering design. This standpoint reinforces the need for integrating engineering, biological, and landscape-ecological solutions when planning sustainable forest and agricultural systems.

A major component of soil microbial communities, both in forested and agricultural areas, is represented by non-spore-forming bacteria, followed by bacilli, with actinomycetes and mold fungi being less abundant (Bogdanov et al., 2015; Malcheva et al., 2015; Naskova, 2016; Plamenov et al., 2016; Yankova et al., 2016; Malcheva et al., 2018; Malcheva et al., 2019; Malcheva, 2020; Malcheva et al., 2020; Malcheva, 2021; Grigorova-Pesheva et al., 2022).. All these main groups of microorganisms are sensitive indicators and should be monitored during the establishment and development of shelterbelts, including under conditions of wind erosion.

The main objective of this study is to develop a sustainable technology for the establishment and cultivation of a shelterbelt with accompanying agricultural crops in the area of the Dobrich State Forest Enterprise (DSFE Dobrich), with a particular emphasis on soil microbiological indicators as sensitive tools for assessing soil biological activity and functional changes. The scientific hypothesis of this study is that the assessment of soil microbiological indicators provides valuable information for evaluating and supporting the sustainable establishment and management of field-protective forest belts combined with accompanying agricultural crops. It is assumed that the combined forest belt–crop system induces measurable changes in soil microbiological indicators, reflecting enhanced soil biological activity and functional stability as a result of altered microclimatic conditions, increased organic inputs, and modified plant–soil–microorganism interactions.

Materials and Methods

Historical Development and International Experience in the Establishment of Shelterbelts

Russia is considered the birthplace of shelterbelts, with protective afforestation reaching a significant scale in the southern Russian steppes at the end of the 18th and the beginning of the 19th century (Melekhov, 1948).

During the 1930s, when severe dust storms threatened the grain-producing regions of the U.S. Midwest, President Franklin D. Roosevelt initiated the ambitious Great Plains Shelterbelt Project. Between 1935 and 1942, an unprecedented 220 million trees were planted across a vast protective belt zone approximately 100 miles wide and stretching 1,150 miles from the Canadian border to northern Texas (Droze, 1977). The program was discontinued after the United States entered World War II. Perhaps because shelterbelts no longer occupy a central place in U.S. political discourse, the long-term effects of the program have never been fully assessed, despite the availability of extensive documentation (Tianshu, 2021). Since the mid-20th century, China has implemented large-scale national programs to combat desertification, within which various types of protective forest plantations, including shelterbelts in agricultural and steppe regions, have been established (FAO, 2002; Kong et al., 2021).

Field-protective forest belts (FPFBs) have a significant role in protecting soils from wind erosion and degradation, as well as in regulating the microclimate and improving agricultural crop yields (Georgiev, 1960; Kort, 1988; Peev, 1990a,b). The first attempts to establish field-protective forest belts in Bulgaria began as early as the 1920s in the region of Southern Dobrudzha, while the large-scale and systematic creation of shelterbelts in Bulgaria started after Council of Ministers Decree No. 236 of 8 March 1951, known as the *"Plan for the Transformation of Dobrudzha"* (Dodev et al., 2023a). At present, a serious problem is the widespread dieback of ash shelterbelts established in Dobrudzha, which creates the need for reconstruction of large areas of various types of degraded shelterbelts (Dodev et al., 2023b, c). The first measures aimed at restoring good condition and ensuring proper management of field-protective forest belts in Bulgaria were implemented during the period 1960–1965 (Marinov et al., 2003).

To fulfill their function, shelterbelts in arable lands must meet a number of specific requirements. Areas with unfavorable climatic conditions, such as those in Dobrudzha, should be considered a priority for implementing this type of agroforestry activity in terms of timing, scale, investment, and production resources. The guiding principle for afforestation in lowland regions should be "afforestation wherever possible." In addition, the supplementation, restoration, or complete reconstruction of many existing shelterbelt systems is necessary. This is required due to their reduced agricultural efficiency in Dobrudzha, which, because of their suboptimal characteristics, is 5–15% below the potential. Some belts even demonstrate a negative agro-productive effect, which is unacceptable (Peev & Hinkov, 2000, 2002).

Furthermore, the destruction of forest shelterbelts in some regions over the past three decades has led to the reoccurrence of adverse phenomena and processes, such as reduced agricultural production and crop failure (Hinkov & Kachova, 2023). Positive trends are identified in the Report on the Implementation of the National Strategy for the Development of the Forest Sector in the Republic of Bulgaria 2013–2020, which states that 24.5 ha of shelterbelts have been restored and 5.4 ha of new forest shelterbelts have been established (https://www.mzh.government.bg/media/filer_public/2018/03/02/nacionalna-strategiya-razvitie-gorski-sektor-2013-2020.pdf).

Selection of Tree Species and Ecological Requirements for Afforestation in Dobrudzha

For the establishment of field-protective forest belts, the selection of appropriate tree and shrub species - those that correspond to the natural conditions of the region - is of exceptional importance. The effectiveness and long-term stability of the belts depend on making the right species choice.

Based on the natural conditions of the Danube Plain and Dobrudzha, the selected species should meet the following key ecological and biological requirements:

• successfully grow and develop under the specific environmental conditions of the region, particularly within the forest-steppe zone;

• exhibit wind resistance and form a deep and strong root system;

• be drought-tolerant in order to withstand prolonged periods of aridity;

• be resistant to cold and snow loads;

• demonstrate rapid height and diameter growth;

• possess relative longevity, which ensures an extended functional lifespan of the belts.

The climatic and soil conditions in Dobrudzha are favorable for the cultivation of the following species: oaks, ash, honey locust, walnut, small-leaved elm, and black locust, with pedunculate oak expected to occupy a leading position in shelterbelt afforestation, followed by Turkey oak and red oak, while companion species may include silver lime, field maple, Tatar maple, manna ash, wild pear, and others (Georgiev, 1960). When selecting tree species, their resistance to glaze ice events characteristic of Dobrudzha should also be considered, with walnut and Turkey oak identified as the most ice-resistant species.

The composition of field-protective forest belts in Northeastern Bulgaria has been shaped by long-term practice aimed at mitigating wind erosion, improving the microclimate, and stabilizing the agrolandscape. According to Dodev et al. (2023a), a relatively wide range of tree species has been used in the existing shelterbelts in the region, with dominant participation of Turkey oak (*Quercus cerris* L.), honey locust (*Gleditsia triacanthos* L.), black locust (*Robinia pseudoacacia* L.), ash (*Fraxinus* spp.), and common walnut (*Juglans regia* L.).

Oak species, and particularly Turkey oak, occupy a leading position in the belts due to their high drought tolerance, good wind resistance, and ability to form a stable shelterbelt structure. An analysis of the health status of the belts indicates that Turkey oak is among the species best adapted to the climatic conditions of Dobrudzha and exhibits relatively high vitality in older stands (Dodev et al., 2023b).

As fast-growing and functionally important species in shelterbelt systems, honey locust and black locust have been widely used, contributing to a more rapid development of the protective effect, especially in the initial stages after establishment. Nevertheless, a deteriorated condition of some black locust and ash stands has been reported, necessitating gradual reconstruction measures (Dodev et al., 2023a,b,c).

The studies further show that ash belts are among the most severely affected by processes of dieback and degradation, whereas Turkey oak and common walnut are distinguished by greater resilience and a longer functional lifespan. Consequently, the need to prioritize resilient oak species and to carefully select companion species in future reconstructions and new afforestation initiatives is emphasized (Hinkov & Kachova, 2023; Dodev et al., 2023b).

In historical forestry practice, the use of fast-growing poplar species as auxiliary components in protective plantings has been reported, due to their rapid biomass production and adaptability to continental and relatively dry conditions. *Populus* spp. has been described as a drought-tolerant and fast-growing species used in shelterbelt systems (Isebrands & Richardson, 2014; Zhang et al., 2006).

In addition, other broadleaved species with supplementary functions occur within the belts, contributing to structural diversity and ecological stability of the agrolandscape. However, the authors note that the lack of timely silvicultural treatments at an early age has led to a deterioration of the initial permeability of many shelterbelts and a reduction in their overall effectiveness (Dodev et al., 2023a).

Microbiological analyses

Soil microbiological analyses included plating on meat peptone agar for non-spore-forming bacteria and bacilli, Czapek–Dox agar for micromycetes (filamentous fungi), and Actinomycetes Isolation Agar for actinomycetes and mineral-nitrogen-assimilating bacteria, each in three replicates. Incubation was carried out in a thermostat under aerobic mesophilic conditions, followed by enumeration of colony-forming units per 1 g of absolutely dry soil (CFU g^{-1}) (Gushterov et al., 1977; Mishustin and Emtsev, 1989; Malcheva and Naskova, 2018; Nustorova and Malcheva, 2020). The total cultivable microbial community and the mineralization coefficient (MC) (ratio of bacteria assimilating mineral nitrogen to the sum of non-spore-forming bacteria and bacilli) were calculated (Mishustin and Runov, 1957; Malcheva and Naskova, 2018; Nustorova and Malcheva, 2020).

Results and Discussion

Table 1. *Participation of Plant Species in Shelterbelts*

Plant Species	Area	
	[ha]	%
Turkey oak (*Quercus cerris* L.)	624.4	33.4
Honey locust (*Gleditsia triacanthos* L.)	399.9	21.4
Black locust (*Robinia pseudoacacia* L.)	318.7	17.1
Manna ash (*Fraxinus excelsior* L.)	307.5	16.5
American ash (*Fraxinus americana* L.)	64.1	3.4
Common walnut (*Juglans regia* L.)	62.9	3.4
Silver lime (*Tilia tomentosa* Moench)	33.7	1.8
Field elm (*Ulmus minor* Mill.)	24.4	1.3
Northern red oak (*Quercus rubra* L.)	16.4	0.9
White mulberry (*Morus alba* L.)	6.9	0.4
Pedunculate oak (*Quercus robur* L.)	4.9	0.3
St. Lucie cherry (*Prunus mahaleb* L.)	1.9	0.1
European hackberry (*Celtis australis* L.)	0.9	0.05
Field maple (*Acer campestre* L.)	0.9	0.05
Common pear (*Pyrus communis* L.)	0.4	0.02
Hungarian oak (*Quercus frainetto* Ten.)	0.2	0.01
Tatar maple (*Acer tataricum* L.)	single trees	
Cherry plum (*Prunus cerasifera* Ehrh.)	single trees	
Blackthorn (*Prunus spinosa* L.)	single trees	
Smoke tree (*Cotinus coggygria* Scop.)	single trees	
Total:	1868.1	100.0

In the area of the DSFE, the shelterbelts occupy a total area of 1868.1 ha. According to the data presented in Table 1, the belts include a relatively large number of tree and shrub species, with the highest representation of Turkey oak, honey locust, black locust, and manna ash.

Selection of the Operational Technology

The selection of a specific technological option for establishing and tending a forest plantation - and in particular a FPFB combined with accompanying agricultural crops - is the most critical stage in the design process. One and the same technology may be implemented in several technological variations depending on the machine accessibility of the area, the purpose of the plantation, the duration and intensity of tending operations, the available tractor - machine fleet, or the possibility of hiring additional machinery.

The most rational option is the one that ensures lower labour and financial costs.

Each technology is divided into four main parts (major operations), arranged according to their sequence:

• Preliminary site preparation - preceding the establishment of the belts and consisting of clearing the area from harvest residues (branches, tops, cut shrubs).

• Primary soil preparation - the slope of the terrain determines the appropriate method of soil cultivation.

• Establishment of the belts - marking planting spots, opening planting pits, and planting the seedlings.

• Tending of the plantations - typically, shelterbelts are tended until the age of 4, or up to 5 years if located within Natura 2000 forest territories.

Initial Data

Table 6 shows that most of the forest enterprise's territory has a low terrain slope. Very steep terrain accounts for only 0.3%. The largest share of the area - about 52.3% - consists of land with a slope up to 5°, which allows for extensive use of mechanization in silvicultural operations. A second major share - approximately 24.2% - belongs to gently sloping areas. The third group - around 18.4% - includes moderately sloping areas, where appropriate machinery and equipment for mechanized soil preparation need to be introduced. From a technological perspective, this does not pose significant difficulties due to the availability of various technologies for afforestation on sloping terrains - terracing, strip planting, etc.

Soil Type and Productivity

Leached Chernozems occupy the largest share - 92.9% of the productive forest area. These soils have formed in places where forest vegetation has been present for long periods. The parent material is loess. Such soils are characterized by great depth, significant accumulation of organic matter (humus) in the upper horizons, and highly favourable conditions for the establishment and growth of shelterbelts. Their soil reaction is nearly neutral, and the water regime is comparatively favourable. The soil texture - sandy-clay - facilitates the use of mechanized technologies.

Size and Shape of the Areas

This factor is of particular importance. The larger the areas, the more rational the use of machinery becomes. It eliminates the need for frequent transportation of tractor-machine units, and in general, efficiency is significantly higher on straight and wide terrains.

Relief and Accessibility

Overall, the relief of the region is flat. From this perspective, there are no obstacles to the implementation of full mechanization.

Selection of the Forest Species

The main forest species selected for the shelterbelt is *Quercus cerris* L. (Turkey oak). *Quercus cerris* L. is a tall tree (up to 35 m) with a massive, spreading crown. The bark is thick, grey-black, coarse, and deeply fissured. The twigs exhibit dense cracks and reddish bark. Young shoots are covered with fine hairs and have a grey-green colour. Leaves are 5–14 cm long, dark green, deeply lobed, and rough, with triangular lobes. The underside is sparsely pubescent, and in autumn the leaves remain green until the first frosts. Acorns mature in two years and reach 3–4 cm in length. The cupule is covered with long, linear-curved scales. In Bulgaria, the species is distributed up to 1200 m a.s.l.

Ecological Requirements of Turkey Oak

This is a light-demanding and drought-resistant species, tolerant of various soil conditions but growing best on deep and fertile soils. It tolerates calcareous substrates and polluted air. Very low winter temperatures may cause frost damage, which weakens tree vitality. Its longevity is relatively short (around 200 years). Due to its fast growth and tolerance to polluted air, it is widely used in parks and mixed stands under drier conditions. It participates extensively in landscape forest plantations, and due to its high drought resistance, its use in shelterbelts should be increased (Vakarelov & Gencheva, 2005).

Selection of Accompanying Agricultural Crops

As accompanying species, watermelon (*Citrullus lanatus (Thunb.) Matsum. & Nakai*) and sweet cherry (*Prunus avium* L.) are selected. According to the accepted classification, watermelon is a fruit vegetable belonging to the Cucurbitaceae family, while cherry is a stone fruit species from the Rosaceae family.

Ecological Requirements of Watermelon

The growth, development, fruiting, and longevity of watermelon depend on climatic and soil conditions. Light, water, and temperature are essential factors for all living organisms. These factors largely depend on latitude, altitude, relief, site exposure, and soil properties. In the present case, the conditions are optimal for watermelon.

Light

Watermelon requires high light intensity; insufficient light results in poor development, longer vegetation period, reduced sugar content, and lower yield.

Temperature

Watermelon is a thermophilic and heat-resistant plant. Seeds germinate at 15–17°C. Optimal growth occurs at 30–45°C. A drop to 15°C slows development, and 5–10°C may kill the plant. Successful pollination requires temperatures above 18°C. At the early growth stages, the plant tolerates low temperatures better. Under high humidity in low tunnels, young plants endure a wide temperature range (2–50°C).

Water and Irrigation

Watermelon has a strong root system, contributing to high drought resistance. To produce 5 kg per 1 m², about 160 litres of water are required. Excessive irrigation before fruit formation results in poor root development and low yields. If irrigation is needed, it should begin at the onset of fruit ripening. Optimal soil moisture is 75–80% of field capacity.

Soil Types

Watermelon is not demanding regarding soil fertility; it grows on poor sandy soils, heavy stony soils, and fertile Chernozems. Cold, clayey, and waterlogged soils should be avoided. Best results occur at pH 6–6.5.

Ecological Requirements of Sweet Cherry

Sweet cherry trees reach heights of 12–15 m, making them suitable as accompanying species. They form sparse, wide-pyramidal to rounded crowns with characteristically tiered branching. At a young age, they have strong vegetative growth and a well-defined leader. With proper care, they bear regularly and abundantly and can live 40–50 years in plantations.

Light

Cherry is highly light-demanding and develops best in open, well-illuminated locations protected from adverse weather. Insufficient light shortens lifespan, reduces yield, and lowers fruit quality. Poor light conditions may result from unsuitable site selection, dense planting, improper crown formation, or shading by trees/buildings.

Temperature

Cherry is a temperate-climate crop with high temperature requirements. It does not tolerate very hot and dry sites; fruits remain small and of poor quality. In hot and dry summers, especially on shallow soils, tree growth is weak and winter frost resistance declines. Fruit buds withstand –24 to –25°C under normal conditions.

Water and Irrigation

Cherry is relatively drought-tolerant and is usually grown under rainfed conditions. Drought tolerance is best expressed on deep, well-drained soils where a strong root system can develop. Cherry does not tolerate waterlogging, frequent irrigation, high groundwater levels, or heavy rainfall during fruit ripening.

Soil Types

Cherry can grow on a variety of soils: slightly podzolic, dark grey and leached cinnamonic forest soils, brown and grey forest soils, carbonate chernozems, alluvial and deluvial meadow deposits, and moderately moist soils.

Description of the Technologies Used for Establishing a Shelterbelt with Accompanying Agricultural Crops

One-year-old *Quercus cerris* (L.) seedlings will be planted. The soil is ordinary (leached) chernozem, with a sandy-clay texture, non-stony, very deep, and formed on loess. The soil depth reaches up to 120 cm, allowing for deep soil preparation. The terrain is flat and has a regular shape.

The main technological variants depend on site conditions - density of stumps, shrubs, and low woody vegetation. Other important factors include agro-technical deadlines and silvicultural requirements for belt establishment. Site machine suitability will be assessed using established criteria.

The site has flat relief and a slope of up to 2°. The soil is non-stony and deep. The mechanical composition is heavy. The site is large, with a regular shape and free access. Based on these characteristics, the site is highly suitable for mechanization, allowing full mechanization of silvicultural operations.

Technological operations will follow this sequence:

• Complete preliminary site preparation

Shrubs are mulched and the terrain is levelled using rotary tillers.

• Planting of seedlings

A two-row planting machine will be used. This method prevents two major problems: root folding during insertion and air pockets at the base of the planting slit. The planting scheme will be 3 × 0.5 m. Watermelons (*Citrullus lanatus (Thunb.) Matsum. & Nakai*) will be sown between the rows by direct seeding, while the two outer rows will be planted with cherries (*Prunus avium* L.) at 6 m spacing.

• Tending of shelterbelts

Due to frequent droughts in Dobrudzha, manual hoeing within rows will continue for five years, especially since much of the enterprise falls within Natura 2000.

Mulching of Existing Shrub and Woody Vegetation Using a FENDT 926 VARIO TMS Tractor and an AHWI M550 Forestry Mulcher

Mulching will be carried out using a unit consisting of a FENDT 926 VARIO TMS tractor and an AHWI M550 forestry mulcher (Fig. 1) designed for shredding shrub and woody vegetation, as well as logging residues in forest stands and plantations. The vegetation will be shredded into chips and left on the soil to decompose over an area of 34 dka.

Fig. 1. *Photograph of a FENDT 926 VARIO TMS mulching unit and an AHWI M 550 forestry mulcher*

Primary Soil Preparation and Stump Shredding (Deep Mulching) – 40 cm, and Terrain Leveling

Primary soil preparation and using a unit consisting of a FENDT 926 VARIO TMS tractor and a FAE SSM/HP- stump shredding (deep mulching) to a depth of 40 cm, as well as terrain leveling, will be carried out 250 soil mulcher (Fig. 2). This operation will be performed on an area of 34 dka.

Fig. 2. *Photograph of a FENDT 926 VARIO TMS mulching unit and an FAE SSM/HP-250 soil mulcher*

Establishment of the Shelterbelt and Sowing of the Accompanying Agricultural Crop

Afforestation will be performed mechanically using a two-row planting machine. To create suitable conditions for mechanization, provide adequate light, and maximize seedling growth, the planting scheme will consist of six rows for the main field-protective forest belt, with a spacing of 3 m between rows and 0.5 m within the row.

The accompanying agricultural crop is watermelon, which will be established by hill (nest) sowing. Each hill will be sown with 3–4 treated seeds at a depth of 4–5 cm. The spacing between hills within the row will be 60 cm, and the spacing between rows will be 120 cm. After emergence, at the 2–3 leaf stage, the plants will be thinned to 2 plants per hill.

Tending of the Plantation

Five years of tending are planned after planting. Each year, prior to sowing the agricultural crop in the interrows, deep mulching (rotary tilling) will be performed.

The scheme for establishing a field-protective forest belt with an accompanying agricultural crop is presented in Figure 3. The main shelterbelt consists of six rows of *Quercus cerris* L., planted at 3 m between rows and 0.5 m within the row. Watermelon (*Citrullus lanatus (Thunb.) Matsum. & Nakai*) is sown by hill planting in the interrows (1.2 m between rows; 0.6 m between hills). The outer rows are planted with *Prunus avium* at 6 m spacing.

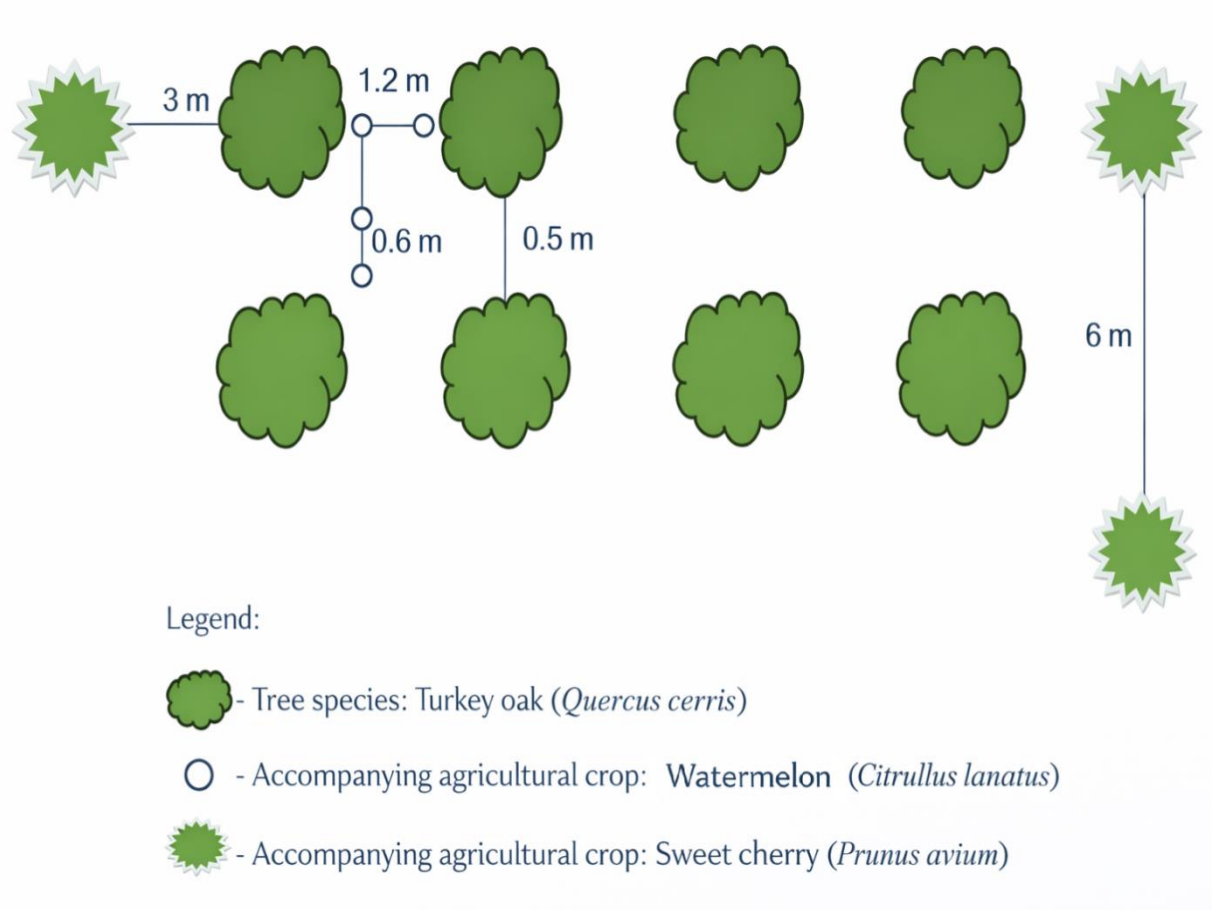

Fig. 3. *Scheme for establishing a field-protective forest belt with an accompanying agricultural crop*

Table 2 presents the technological plan for establishing a field-protective forest belt.

Table 2. *Technological plan for the establishment of shelterbelts*

Year	No	Technological operation	Unit	Work vo-lume	Planned period (from–to)	Wor-king days	Machine unit		Shift productivity Wsh [dka/shift]	Machine -shift days (n)	Required personnel (r)	Man-shift days (m)	Machine-shift cost		Man-shift cost	
							Power unit (model)	Working machine (model)					per 1 dka (Hm)	Total (Hm)	per 1dka (Hc)	Total (Hc)
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
I	1	Mulching of woody–shrub vegetation and logging residues.	dka	34	04.III-04.III	1	Fend 926 VARIO	AHWI M 550	31.17	1	1	1	0.032	1.091	0.032	1.091
	2	Deep rotary tillage and stump shredding – 40 cm.	dka	34	05.III-07.III	3	Fend 926 VARIO	FAE SSM/HP-250	11.76	1	1	1	0.085	2.891	0.085	2.891
	3	Planting of the crop.	dka	34	08.III-08.III	1	Fend 926 VARIO	SLCH - 2	36	1	5	5	0.028	0.944	0.139	4.722
	4	Inter-row rotary tillage.	dka	24	4.V-6.V	3	Fend 926 VARIO	FAE SSM/HP-250	11.76	1	1	1	0.085	2.891	0.085	2.891
	5	Watermelon sowing.	lm	8100	7.V-9.V	3	-	manual	3300	-	-	10	-	-	1.513	51
	6	Inter-row weeding.	lm	18000	30.V-.6.VI	6	-	manual	3300	-	-	10	-	-	1.513	51
	7	Inter-row weeding.	lm	18000	25.VI-.31.VI	6	-	manual	3300	-	-	10	-	-	1.513	51
	8	Inter-row weeding.	lm	18000	10.VII-.15.VII	6	-	manual	3300	-	-	10	-	-	1.513	51
	9	Harvesting	dka	24	03.VIII-20.VIII	17	Fend 926 VARIO	Trailer	-	-	-	-	-	-	-	-
	10	Disc harrowing	dka	24	7.IX	0.18	Fend 926 VARIO	Disc harrow Alpler – 2,5 m	160	1	1	1	0.006	0.176	0.006	0.176

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
II	11	Disc harrowing	dka	24	01.VI	0.18	Fend 926 VARIO	Disc harrow Alpler – 2,5 m	160	1	1	1	0.006	0.176	0.006	0.176
	12	Inter-row weeding.	lm	9900	01.VI-03.VI	3	-	manual	3300	-	-	10	-	-	1.513	51
	13	Inter-row rotary tillage.	dka	24	4.V-6.V	3	Fend 926 VARIO	FAE SSM/HP-250	11.76	1	1	1	0.085	2.891	0.085	2.891
	14	Watermelon sowing.	lm	8100	7.V-9.V	3	-	manual	3300	-	-	10	-	-	1.513	51
	15	Inter-row weeding.	lm	18000	30.V-.6.VI	6	-	manual	3300	-	-	10	-	-	1.513	51
	16	Inter-row weeding.	lm	18000	25.VI-.31.VI	6	-	manual	3300	-	-	10	-	-	1.513	51
	17	Inter-row weeding.	lm	18000	10.VII-.15.VII	6	-	manual	3300	-	-	10	-	-	1.513	51
	18	Harvesting	dka	24	03.VIII-20.VIII	17	Fend 926 VARIO	Trailer	-	-	-	-	-	-	-	-
	19	Disc harrowing	dka	24	7.IX	0.18	Fend 926 VARIO	Disc harrow Alpler – 2,5 m	160	1	1	1	0.006	0.176	0.006	0.176
III	20	Disc harrowing	dka	24	01.VI	0.18	Fend 926 VARIO	Disc harrow Alpler – 2,5 m	160	1	1	1	0.006	0.176	0.006	0.176
	21	Inter-row weeding.	lm	9900	01.VI-03.VI	3	-	manual	3300	-	-	10	-	-	1.513	51
	22	Inter-row rotary tillage.	dka	24	4.V-6.V	3	Fend 926 VARIO	FAE SSM/HP-250	11.76	1	1	1	0.085	2.891	0.085	2.891
	23	Watermelon sowing.	lm	8100	7.V-9.V	3	-	manual	3300	-	-	10	-	-	1.513	51

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	24	Inter-row weeding.	lm	18000	30.V-.6.VI	6	-	manual	3300	-	-	10	-	-	1.513	51
	25	Inter-row weeding.	lm	18000	25.VI-.31.VI	6	-	manual	3300	-	-	10	-	-	1.513	51
	26	Inter-row weeding.	lm	18000	10.VII-.15.VII	6	-	manual	3300	-	-	10	-	-	1.513	51
III	27	Harvesting	dka	24	03.VIII-20.VIII	17	Fend 926 VARIO	Trailer	-	-	-	-	-	-	-	-
	28	Disc harrowing	dka	24	7.IX	0.18	Fend 926 VARIO	Disc harrow Alpler – 2,5 m	160	1	1	1	0.006	0.176	0.006	0.176
	29	Disc harrowing	dka	24	01.VI	0.18	Fend 926 VARIO	Disc harrow Alpler – 2,5 m	160	1	1	1	0.006	0.176	0.006	0.176
	30	Inter-row weeding.	lm	9900	01.VI-03.VI	3	-	manual	3300	-	-	10	-	-	1.513	51
	31	Inter-row rotary tillage.	dka	24	4.V-6.V	3	Fend 926 VARIO	FAE SSM/HP-250	11.76	1	1	1	0.085	2.891	0.085	2.891
	32	Watermelon sowing.	lm	8100	7.V-9.V	3	-	manual	3300	-	-	10	-	-	1.513	51
	33	Inter-row weeding.	lm	18000	30.V-.6.VI	6	-	manual	3300	-	-	10	-	-	1.513	51
	34	Inter-row weeding.	lm	18000	25.VI-.31.VI	6	-	manual	3300	-	-	10	-	-	1.513	51
	35	Inter-row weeding.	lm	18000	10.VII-.15.VII	6	-	manual	3300	-	-	10	-	-	1.513	51
	36	Harvesting	dka	24	03.VIII-20.VIII	17	Fend 926 VARIO	Trailer	-	-	-	-	-	-	-	-
IV	37	Disc harrowing	dka	24	7.IX	0.18	Fend 926 VARIO	Disc harrow Alpler – 2,5 m	160	1	1	1	0.006	0.176	0.006	0.176
	38	Disc harrowing	dka	24	01.VI	0.18	Fend 926 VARIO	Disc harrow Alpler – 2,5 m	160	1	1	1	0.006	0.176	0.006	0.176
	39	Inter-row weeding.	lm	9900	01.VI-03.VI	3	-	manual	3300	-	-	10	-	-	1.513	51

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
V	40	Inter-row rotary tillage.	dka	24	4.V-6.V	3	Fend 926 VARIO	FAE SSM/HP-250	11.76	1	1	1	0.085	2.891	0.085	2.891
	41	Watermelon sowing.	lm	8100	7.V-9.V	3	-	manual	3300	-	-	10	-	-	1.513	51
	42	Inter-row weeding.	lm	18000	30.V-.6.VI	6	-	manual	3300	-	-	10	-	-	1.513	51
	43	Inter-row weeding.	lm	18000	25.VI-.31.VI	6	-	manual	3300	-	-	10	-	-	1.513	51
	44	Inter-row weeding.	lm	18000	10.VII-.15.VII	6	-	manual	3300	-	-	10	-	-	1.513	51
	45	Harvesting	dka	24	03.VIII-20.VIII	17	Fend 926 VARIO	Trailer	-	-	-	-	-	-	-	-
	46	Disc harrowing	dka	24	7.IX	0.18	Fend 926 VARIO	Disc harrow Alpler – 2,5 m	160	1	1	1	0.006	0.176	0.006	0.176

After determining the technological operations and the required number of machine-shifts and man-shifts, the composition of the machine–tractor fleet for the designed afforestation technology (Table 3) and the composition of the planned labor resources (Table 4) are presented in tabular form.

Table 3. *Composition of the planned machine–tractor fleet*

No	Name and brand of the tractor and technological machine	Required number for individual months											
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
First year													
1	FENDT 926 VARIO TMS	-	-	1	-	-	-	-	-	-	-	-	-
2	FAE SSM/HP-250	-	-	1	-	-	-	-	-	-	-	-	-
3	AHWI M550	-	-	1	-	-	-	-	-	-	-	-	-
4	AHWI SF 1000	-	-	1	-	-	-	-	-	-	-	-	-
5	Disc harrow Alpler – 2.5 m	-	-	-	1	1	1	-	-	-	-	-	-
6	SLCH - 2	-	-	1	-	-	-	-	-	-	-	-	-
Second year													
7	FENDT 926 VARIO TMS	-	-	-	1	-	-	-	-	1	-	-	-
8	FAE SSM/HP-250	-	-	-	1	-	-	-	-	1	-	-	-
9	Disc harrowAlpler – 2.5 m	-	-	-	1	-	-	-	-	1	-	-	-
Third year													
10	FENDT 926 VARIO TMS	-	-	-	1	-	-	-	-	1	-	-	-
11	FAE SSM/HP-250	-	-	-	1	-	-	-	-	1	-	-	-
12	Disc harrowAlpler – 2.5 m	-	-	-	1	-	-	-	-	1	-	-	-
Fourth year													
13	FENDT 926VARIO TMS	-	-	-	1	-	-	-	-	1	-	-	-
14	FAE SSM/HP-250	-	-	-	1	-	-	-	-	1	-	-	-
15	Disc harrowAlpler – 2.5 m	-	-	-	1	-	-	-	-	1	-	-	-
Fifth year													
16	FENDT 926VARIO TMS	-	-	-	1	-	-	-	-	1	-	-	-
17	FAE SSM/HP-250	-	-	-	1	-	-	-	-	1	-	-	-
18	Disc harrow Alpler – 2.5 m	-	-	-	1	-	-	-	-	1	-	-	-

Table 4. *Composition of the planned labor resources*

No.	Name and brand of the tractor and technological machine	Required number for individual months											
		I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
First year													
1	Tractor operator	-	1	1	1	1	1	-	-	-	-	-	-
2	Planters	-	-	4	-	-	-	-	-	-	-	-	-
3	Hoeing workers	-	-	-	10	10	10	10	10	-	-	-	-
Second year													
4	Tractor operator	-	-	-	1	1	1	1	1	1	-	-	-
5	Hoeing workers	-	-	-	10	10	10	10	10	-	-	-	-
Third year													
6	Tractor operator	-	-	-	1	1	1	1	1	1	-	-	-
7	Hoeing workers	-	-	-	10	10	10	10	10	-	-	-	-
Fourth year													
8	Tractor operator	-	-	-	1	1	1	1	1	1	-	-	-
9	Hoeing workers	-	-	-	10	10	10	10	10	-	-	-	-
Fifth year													
10	Tractor operator	-	-	-	1	1	1	1	1	1	-	-	-
11	Hoeing workers	-	-	-	10	10	10	10	10	-	-	-	-

As can be seen from the tables above, two tractors will be used, and only for a relatively short period - approximately 2–3 months. The funds required for renting the machinery will therefore have to be secured and invested within a short time frame.

The composition of the labor resources is also economically inefficient.

The technological plan shows that soil preparation and afforestation will be carried out in a mechanized manner. The tending operations will be conducted over a period of five calendar years.

Determination of the degree of mechanization

The degree of mechanization is determined for aggregated operations and for the technology as a whole. It is calculated using the following formula:

$$C = \frac{V_m}{V_o} \times 100\%$$

where V is the volume of work performed mechanized (dka), and V_o is the total volume of work performed (dka).

The degree of mechanization by aggregated operations and for the entire technology at the site is as follows:

- soil preparation - C = 100.00%;
- afforestation - C = 100.00%;
- tending - C = 84.0%;
- average – C = 87.00%.

Occupational safety when working with machinery

Due to the relatively harsh conditions of production activities, occupational safety is of crucial importance in forestry operations. Therefore, compliance with the statutory occupational health and safety regulations is strongly recommended.

Economic indicators

There are several basic rules for determining technological operations. It is important not only to reduce labor costs and increase productivity, but also to improve working conditions, reduce labor intensity, and comply with the fundamental silvicultural requirements (Table 5).

Table 5. *Evaluation of the technological project per dka*

No.	Technological operation	Machine unit		Unit price, BGN
		Power unit (model)	Working machine (model)	
1	2	3	4	5
1	Mulching of existing woody–shrub vegetation and logging residues.	Fend 926 VARIO	AHWI M 550	-70
2	Primary soil preparation (deep rotary tillage) and stump shredding – 40 cm.	Fend 926 VARIO	FAE SSM/HP-250	-400
3	One-year-old seedling plants + transport and handling			-58
4	Planting of the crop	Fend 926 VARIO	SLCH - 2	-50
5	Inter-row disc harrowing	Fend 926 VARIO	Disc harrow Alpler – 2,5 m	-15
6	Watermelon sowing	-	manual	-56
8	Watermelon seeds			-30
9	Weeding	-	manual	-46
10	Estimated watermelon yield per dka – 3,000 kg			+ 1000

According to the proposed scheme (Fig. 3) for establishing a field-protective forest belt with an accompanying agricultural crop, preliminary microbiological analyses were conducted on forest soils (Chernozems) under Turkey oak (*Quercus cerris* L.) and cultivated soils (Chernozems) under watermelon (*Citrullus lanatus (Thunb.) Matsum. & Nakai*) and sweet cherry (*Prunus avium* L.) in spring, at a depth of 0–20 cm. Although forest soils often exhibit lower overall microbial activity and slower mineralization of organic matter due to the accumulation of stable humus, recalcitrant compounds, and the absence of mechanical aeration and fertilization, the structure of the microbial community differs to some extent from that of agricultural soils. Forest soils are characterized by a higher relative contribution of non-spore-forming bacteria, actinomycetes, and filamentous fungi, whereas agricultural soils are dominated by spore-forming bacteria (*Bacillus* spp.), adapted to frequent mechanical disturbance, stress conditions, and fertilization with microbial fertilizers (Fig. 4). Mineralization activity is highest under *Citrullus lanatus* (Thunb.) Matsum. & Nakai. Soil microbiological indicators are sensitive parameters and should be monitored both before the establishment of shelterbelts and thereafter, considering their seasonal and annual dynamics. We consider that the establishment of a field-protective forest belt with accompanying agricultural crops will increase soil biogenicity.

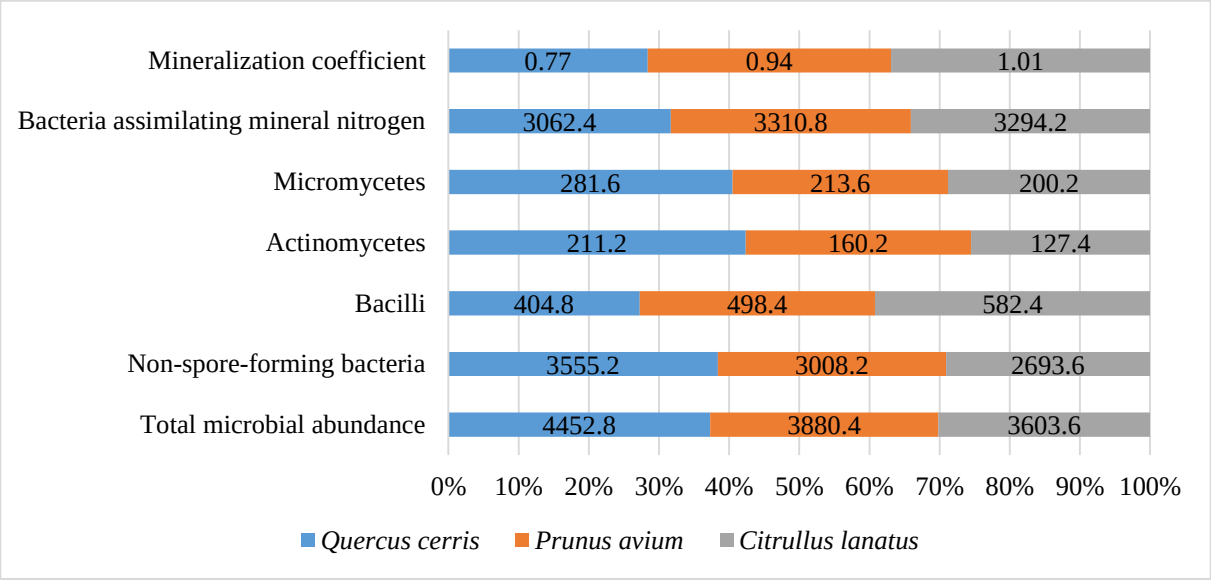

Fig. 4. *Abundance (×10³ CFU g⁻¹), composition, and activity (MC) of soil microorganisms*

Similar trends, with a predominance of non-spore-forming bacteria, followed by spore-forming bacteria (bacilli) and a lower contribution of mycelial forms - actinomycetes and filamentous fungi have also been reported by other authors in studies of forest and agricultural soils. These studies further indicate that the mineralization and enzymatic activities of microorganisms depend not only on their abundance but also on a complex of factors, including soil temperature and moisture, soil pH (forest soils are more often acidic, which favors the development of filamentous fungi), nutrient availability (mineral and organic fertilization at appropriate rates increases soil biogenicity), vegetation type (the decomposition of coniferous litter is more constrained compared to the decomposition of dead forest litter from broadleaved tree species), soil texture, altitude, and other factors (Susyan et al., 2006; Bogdanov et al., 2015; Malcheva et al., 2015; Naskova, 2016; Naskova et al., 2016;

Plamenov et al., 2016; Qi et al., 2016; Yankova et al., 2016; Malcheva et al., 2018; Malcheva et al., 2019; Malcheva, 2020; Malcheva et al., 2020; Malcheva, 2021; Grigorova-Pesheva et al., 2022; Malcheva et al., 2023; Malcheva et al., 2024; Malcheva, 2025).

Conclusion

The area of shelterbelt forest belts within the territory of the Dobrich State Forestry Enterprise amounts to 1,868.1 ha. Approximately 52% of them are over 50 years old. Among the tree species used in the existing shelterbelts, the highest proportions are represented by Turkey oak (*Quercus cerris* L.), honey locust (*Gleditsia triacanthos* L.), manna ash (*Fraxinus ornus* L.), black locust (*Robinia pseudoacacia* L.), and common walnut (*Juglans regia* L.). The belts were originally established with a permeable structure; however, due to the lack of silvicultural treatments at early developmental stages and the encroachment of shrub species, most of them are currently non-permeable, which hinders their proper functioning. A technological scheme is proposed, including full soil preparation, followed by planting of forest seedlings and sowing of an accompanying agricultural crop.The advantages of the proposed technological scheme include shortened agrotechnical periods for soil preparation, a significant reduction in labor costs, and the creation of prerequisites for additional income.

Forest soils under Turkey oak are characterized by a higher total abundance of microorganisms and a greater relative proportion of non-spore-forming bacteria, actinomycetes, and microscopic fungi, whereas cultivated soils under cherry and especially under watermelon exhibit a higher proportion of spore-forming bacteria and more intensive mineralization processes.

Microbiological indicators should be studied dynamically before and during the establishment of field-protective forest belts. We consider that their combination with accompanying agricultural crops will enhance soil biogenicity and soil fertility.

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120 Years of Organized Soil Erosion Control in Bulgaria: A Review

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Received: 15 November 2025 *Accepted: 5 February 2026*

Abstract

In 2025, Bulgaria celebrated 120 years of organized soil erosion control. The beginning of this activity is considered to be 1905, marked by the French floodplain control inspector Félix Vogeli. The achievements of Bulgaria over these 120 years provide a valuable example of sustained efforts to protect soils, restore natural vegetation, and manage agricultural land sustainably. Throughout this period, Bulgaria's agrarian policy has undergone numerous changes. Various erosion control policies were implemented, particularly during the 1950s and 1970s, followed by more recent reforms linked to European Union policies and strategies aimed at preventing soil degradation. Overall, a significant improvement in soil conditions has been observed, largely due to the restoration of extensive areas of natural, predominantly forest vegetation and the adoption of good agricultural practices that minimize soil disturbance during cultivation.

Keywords: soil erosion control, Bulgaria, review

Introduction

In 2025, Bulgaria marked 120 years of organized efforts to control soil erosion, dating back to 1905, when the Bureau for the Strengthening of Floodplains and Afforestation was established in the city of Kazanlak. Over the past 120 years, erosion control activities in the country have passed through several distinct stages. Despite changes in policies, approaches, and institutional frameworks, substantial progress has been achieved. These successes are primarily attributable to the restoration of natural vegetation and the implementation of effective measures to protect soils from degradation**.** Soil erosion is the most significant soil degradation process on the territory of Bulgaria. This is a result of natural physical and geographical conditions and the way of land use. Agriculture and forestry in our country suffer great losses from the effects of soil erosion. In other sectors of the economy, these harmful consequences related to erosion are very different. Soil erosion annually takes away valuable agricultural lands, which remain wasteland or have lost their soil fertility to one

degree or another. The fact is that arable lands in Bulgaria occupy relatively small areas, therefore soil protection and use is the essential and primary important (Stanev, 1979).

The protection of land from the effects of water and wind erosion is a major problem for the future development of agriculture in our country. Naturally, this concerns a natural national wealth, such as soil. It is systematically destroyed and irretrievably carried away into rivers and seas, thus destroying the main means of producing food, fodder, and all related stocks in our agriculture.

Looking into the distant past

From a historical point of view, the destruction of natural vegetation on the territory of Bulgaria began thousands of years ago. This is a long process that began with the emergence of the first settlements on our territory, as a result of human activity and the first forms of agriculture, animal husbandry, crafts, mining, etc. This was the history how agriculture developed during the Middle Ages when forest areas and lawns were converted into agricultural lands.

At the end of the 14 century after the conquest of Bulgaria by the Ottoman Empire, further development of forest and mountain areas began. This was the period when the fertile plain lands were taken by Ottoman feudal lords, and then part of the Bulgarian population was forced to look for land in the mountainous regions (Biolchev, 1953). In these places, due to unfavourable topographic conditions, the soils quickly become impoverished, washed away and in a short time became unsuitable for further agricultural cultivation. This forced the mountain dwellers to constantly search for new lands for agricultural purposes, which they obtained by destroying forest areas.

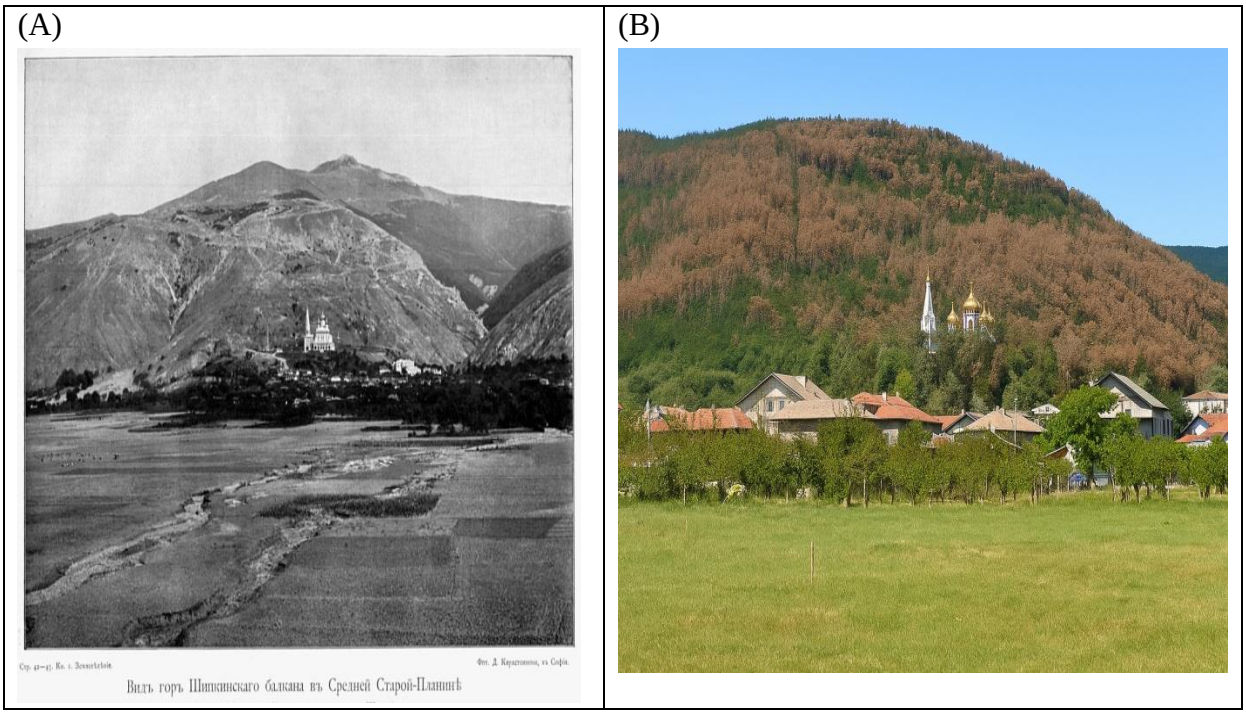

Fig. 1. *The Shipka peak in Balkan mountain, in year 1902 (A) and in 2025 (B).*

The extent of forest destruction was initially limited, but together with population growth, these dimensions reached their maximum magnitude after liberation at the end of the

19th century. In mountainous areas, the activities of the *Yuruk* and *Karakachan* tribes destroyed large forest areas in the mountains through fires in order to have pastures for their herds. Throughout the Ottoman rule, no measures were taken to restore the destroyed forest vegetation, nor to control erosion, which in many places was already in a fairly advanced state. Such measures were far from the policy of the socially and economically backward Ottoman Empire.

After the liberation in 1878, the rapid economic development of our country began, when forests were still being cut down due to the need for timber. This led to a severe deterioration of the vegetation in the watersheds of the mountain watercourses, turning them into typical torrents.

Beginning of the organised soil erosion control in Bulgaria

Afforestation in the country began with artificial reforestation of degraded lands due to erosion. Completely different sites for reforestation and afforestation of barren and degraded lands were treated in the same way and the ecological requirements of different forest tree species were not taken into account. Some good results were obtained only with acacia tree afforestation in the Danubian Plain. Afforestation of degraded lands had occasional and temporary success (Alexandrov et al., 2020).

In 1905, the Bulgarian government, and Ministry of Agriculture and State Property, call for help to the government of France, a country with the greatest success in the management against floodplains, fortification measures and erosion control, with a request for assistance to Bulgaria. In the same year, the first Bureau for the Strengthening of Floodplains and Afforestation was opened in the town of Kazanluk by the frenchman Félix Vogeli, an inspector for the strengthening of floodplains in France. In six years, Félix Vogeli created four sections of the "Bureau" in towns of Sliven, Kyustendil, Tran and Karlovo (1911). They grew up to 38, and in 1948 the "People's Republic of Bulgaria" closed them and created the State Forestry Company (SFC). The successor to the "Bureau" in Kazanlak was SFC-Kazanlak (Tsavkov et al., 2025).

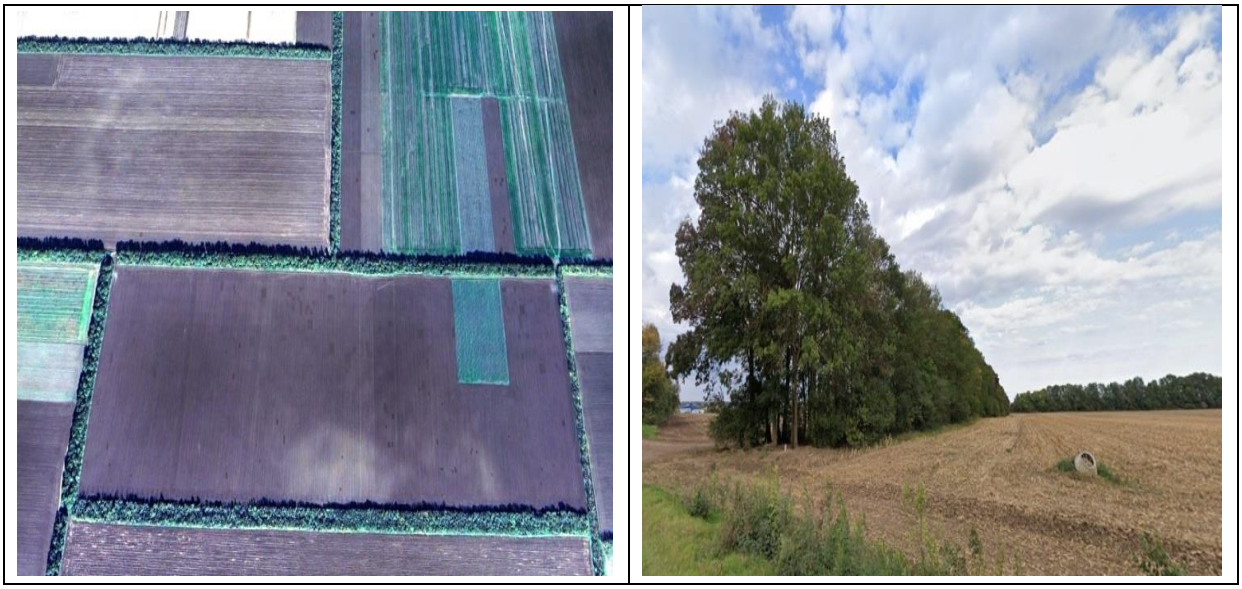

Fig. 2. *Field protection forest belts in Dobrudja to prevent wind erosion (photos: Google-earth)*

After the Second World War and the years after it, the People's Republic of Bulgaria was still strongly affected by erosion in mountainous, forest and pastures areas and it was less affected in agricultural lands. During collectivization, when private property was abolished and the land was consolidated, a process of removing the natural field borders and clearing the natural vegetation around the agricultural lands began, as a result of which erosion also began to increase in agricultural lands. Then the introduction of mechanized equipment in agriculture began, and yields increased, but so did erosion. It is a well-known fact that soil scientist Academician Ivan Stranski was criticized for shallow ploughing by the then chairman of the Bulgarian Communist Party, Valko Chervenkov, because in his textbook from 1940 he recommended shallow ploughing (Chervenkov, 1952).

Soil erosion control during the period 1950-1990

In 1950, a scientific expedition on agroforestry reclamation was organized, which carried out detailed route studies on soil erosion in the cultivated lands of the main hilly and plain regions of the country. By Decree No. 236 of the Central Committee of the Bulgarian Communist Party and the Council of Ministers of the People's Republic of Bulgaria (1951), a plan was adopted for the construction of state and field protection forest belts in Dobrudzha as a measure to prevent droughts and wind erosion in this region. These issues were studied at the Dobrudzha Research Institute near the town of General Toshevo.

In 1955, the Decree of the Council of Ministers of the Republic of Bulgaria "Preventing Erosion on Cultivated Lands" was issued, which marked the beginning of research work on soil erosion in the entire country, by organizing a department on soil erosion at the Institute of Soil Science "N. Poushkarov" in Sofia. This department is the main scientific unit for studying the given issue. In 1956, a section on Soil Erosion was established at the Soil Science Institute at the Bulgarian Academy of Sciences and three experimental fields for erosion studies were opened as well.

Lectures on soil erosion and its control were included in the students teaching programs of the "G. Dimitrov" Agricultural Institute, the "V. Kolarov" Agricultural Institute and the state agricultural technical schools. In the same year, scientific work on soil erosion also began at the Karnobat Agricultural Research Institute, the Tobacco Station in Djebel and the Institute of Forage in Pleven. In 1958, scientific work on soil erosion began at the Institute of Viticulture and Enology in Pleven. The first erosion research stations were organized in the village of Mirkovo and the city of Pleven (later only the one in Mirkovo remained). In 1963-1964, scientific work on soil erosion began at the Institute of Viticulture and Enology in Troyan and at the Agricultural Research Centre in Kardzhali, and an erosion research station was organized in the village of Suhodol. In the second half of the 1960s, complex erosion studies were carried out in the watershed of the Topolnitsa river reservoir under the methodological guidance of prof. Biolchev and prof. V. Koinov, where 6 *limngraph* stations were installed at different types of land use (forests, high-mountain and low-mountain pastures, and agricultural fields). During the period 1970-1979, an experimental station for preventing erosion was established in the city of Ruse with an experimental field for erosion research in the village of Trastenik. An experimental field for erosion research was organized near town of Topolovgrad. Field plot and model erosion studies were carried out under various soil types, climatic and economic conditions (Rousseva et al., 2010).

To improve the soil erosion control management in our country, the State Council adopted Resolution No. 21 of July 9, 1975 "Basic Provisions for Improving the Management against Erosion in P.R. Bulgaria". According to this government document, further work on preventing soil erosion will be conducted in a unified and coordinated manner on the basis of a National Long-Term Program (Stanev, 1979). In 1977, the Methodology for Developing a National Program for Erosion Control was developed and standards for designing anti-erosion measures were prepared (Biolchev et al., 1977). In 1979, 6 national standards (BDS) on soil erosion were developed. For most of the activities related to erosion control and other degradation processes, large and compact areas are required. Until 1989, they were carried out in watersheds covering vast territories - all types of land use (fields, meadows and pastures). Since the restoration of ownership rights over agricultural land after 1990, this situation of soil erosion research had been changed (NAP, 2014).

Soil erosion control since 1990

Since 1990, erosion studies continued under new modern ways as various models for predicting erosion processes were developed. After 2000, also new GIS models were introduced to supplement and harmonize the methodology for assessing and mapping the factors and intensity of water and wind erosion of the soil.

Studies were carried out on optimal practices for anti-erosion land use, territorial organization, organic farming and ecological soil protection, appropriate crops and crop rotations, machines, devices and technologies, water-saving and soil protection practices, etc. (Rousseva, et al., 2010).

In 2019, the World Soil Day, dedicated to soil erosion control, “Stop Soil Erosion, Save Our Future” was celebrated on December 5th around the world, as well as in Bulgaria. Restriction of soil erosion is a key to achieving the Millennium Development Goals such as zero hunger, good health and well-being, access to clean water, innovation in industry, climate action, responsible consumption, and supporting life on land and underwater (Rousseva, 2020).

Nowadays, new agricultural machines are entering the markets that are ecologically friendly to the soil. Conservation agriculture equipment (no-till, strip-till, minimum-till, mulchers, etc.) for tillage and devices related to the application of non-traditional soil cultivation technological operations in the technologies for growing main crops.

Under the EU's Common Agricultural Policy (CAP), soil protection aspects are part of the requirements for good agricultural and environmental condition. Efforts are focused on restricting soil erosion, preserving and improving soil organic matter, and avoiding compaction.

Nowadays, about 85% of the soils in the country are affected by erosion processes (Atanassova, 2021). According to data from the Executive Environmental Agency (ExEA, 2024), in the period 2015-2021, the areas affected by surface water erosion and soil losses increased. Compared to the previous year, in 2021, a slight increase in the intensity of surface water erosion was observed. In the period 2015-2021, the areas affected by wind erosion remained relatively constant. Compared to the previous year, in 2021, a decrease in the intensity of wind erosion was observed.

In 2023, the areas with agricultural land that have a low erosion risk (< 5 t/ha/y) are 1,738,635 ha, those with moderate (5.01-20 t/ha/y) and high risk (> 20 t/ha/y) are 1,989,243 ha and 2,007,111 ha, respectively. With this regard, only the area of arable land with low erosion risk is 1,432,427 ha, with moderate risk is 1,476,175 ha, and with high risk is 726,237 ha (ExEA, 2025). The average annual intensity of sheet water erosion on agricultural lands varies from 10.8 t/ha/y on pastures and 11.1 t/ha/y on arable land to 13.7 t/ha/y on areas occupied by other types of agricultural crops.

Compared to 2022, in 2023 there was a slight increase in the areas at risk of wind erosion, while soil losses slightly decreased. Data on the distribution of the country's territory by degrees of wind erosion in 2023 show that (37.2%) of arable land is at low to moderate risk (0.2-0.5 t/ha y), (ExEA, 2025).

The risk of irrigation erosion is relatively small, affecting irrigated lands with a slope of more than 6%, most of which have been abandoned since 1990. The area of irrigated lands in Bulgaria until 1990 was about 25% of the arable land. As a result of in-depth research, it has been established that the risk of irrigation erosion is highest with gravity furrow irrigation, varying from 2.5 to 8.6 t/ha for one water supply and that the application of rain-fed irrigation can significantly reduce soil losses (Rousseva, 2006). In recent years, drip irrigation has become widespread, in which there is no soil loss from irrigation.

Classification of anti-erosion measures (practices) in Bulgaria.

The entire complex of soil protection equipment, technological operations, methods and technologies forms the system of measures (practices) to control soil erosion (Dimitrov et al., 2014).

The measures of this system can be structured into the following main groups:

I. Organizational and economic measures.

In the system of anti-erosion measures, the leading role belongs to the organization of the territory, which is based on the correct placement of agricultural land and crop rotation fields and production (team) plots on the territory with erosion risk. Such placement is carried out taking into account the features of the relief, the exposure of the slopes, soils and the degree of their erosion risk in order to create the best conditions for agricultural engineering, primarily erosion control and mechanization of agricultural production processes, designing agro-technical facilities, forestry hydrological and technical measures.

II. Agro-technical measures.

Agro-technical measures include all anti-erosion technological operations and technologies for soil cultivation, sowing and planting of agricultural crops and their cultivation. It can be included also anti-erosion crop rotations, selection of alternative and energy crops for non-fertile agricultural lands.

The following anti-erosion agricultural practices (methods) are used in our country: contour cultivation of sloping arable lands, furrow-ridge ploughing, flat-cut cultivation, runoff retention furrows, cutting with course formation, terracing, construction of grassed runoff collectors, mulching, - orienting the rows in the horizontal direction, terracing, grassing the inter-rows, mulching and green fertilizing, minimal and zero tillage of the soil, and others.

III. Biological measures.

Biological (agroforestry) measures include: field protection and water-regulating forest belts and plantations on offshore lands and in the river network, as well as anti-erosion grassing.

Forest belts are placed in accordance with the existing instructions for afforestation of protected belts, contributing to the retention of surface runoff and reducing its destructive force. In flat terrain, to protect the soil from wind erosion, longitudinal field protection forest strips are laid, located transversely to the direction of the prevailing winds.

IV. Land reclamation and technical measures.

Land reclamation and technical measures are the permanent anti-erosion measures, which use land reclamation and technical and hydro-technical facilities to protect arable lands with a slope of more than 6-7^{o} from erosion and to prevent gully and stream bank erosion in the river network.

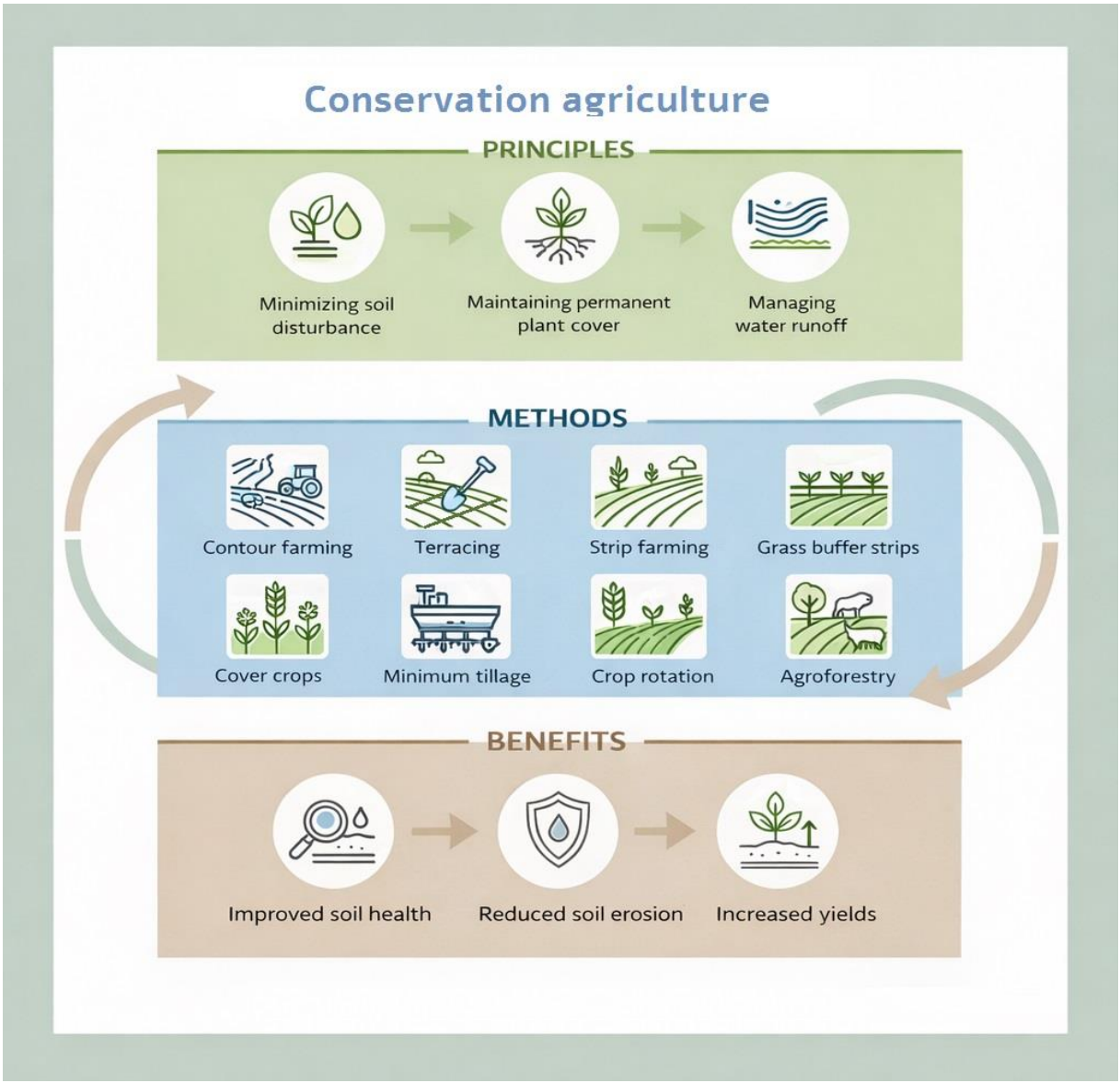

Fig. 3. *Scheme of basic principles, methods and benefits in the implementation of conservation agriculture.*

All practices from the system of measures to prevent erosion must be interconnected and complement each other so that they can be applied comprehensively and simultaneously on the entire territory of a given farm.

According to the national report on the state and protection of the environment of the Executive Agency for the Environment (ExEA, 2024 and 2025), in recent years a consistent policy has been implemented to limit the erosion process in several directions:

1. Annual monitoring conducted by the Environmental Agency for the entire country, the data from which are used to plan land use in a way that limit erosion processes;

2. Informing and assisting agricultural producers in planning the use on a given farm by the regional structures of the Ministry of Agriculture (MA);

3. Compliance with Good Agricultural and Environmental Conditions (GAEC);

4. Support for agricultural producers through compensatory payments for activities limiting the erosion process (MA).

Good agricultural and environmental conditions (GAEC) of agricultural lands are implemented using specially developed standards. They are part of the system of ex ante conditionality (Article 12 of Regulation (EU) 2021/2115 of the European Parliament and of the Council of 2 December 2021), which aims to contribute to the development of sustainable agriculture by raising beneficiaries' awareness of the need to implement these standards.

Strategies and policies to prevent soil erosion in the EU

The EU strategy to prevent soil erosion is based on the EU Soil Strategy to 2030 (2021), which aims for healthy soils by 2050 (Fig. 4). Key initiatives include the Soil Monitoring Act, a new legislative instrument for a harmonised approach across the EU to monitoring and restoring soil health, was adopted on 23 October 2025 (Council of the European Union, 2025). The new directive introduces a pan-European methodology for assessing the physical, chemical and biological status of soils.

The EU Mission: A Soil Deal for Europe, part of the Horizon Europe programme, has also been adopted, aiming to restore soil health by 2030. The EU strategy integrates policies such as the Biodiversity Strategy and the Common Agricultural Policy (CAP) and uses tools such as the EU Soil Observatory to improve data and knowledge on soil health, supporting sustainable soil use and restoration.

The EU Biodiversity Strategy for 2030 states that it is essential to increase efforts to protect soil fertility, reduce soil erosion and increase soil organic matter content through sustainable soil management practices. According to expert estimates, between 61 % and 73 % of agricultural soils in the EU are affected by erosion, loss of organic carbon, excess nutrient (nitrogen) content, compaction or secondary salinization (or a combination of these threats) (Council of the European Union, 2023).

Erosion control policies in Bulgaria and the EU can prevent imbalances in competitiveness and broaden societal and economic benefits. The Republic of Bulgaria as an EU member has access to larger budgets, which can also provide significant funding for projects and research to protect soils from degradation. Erosion control policies need to take these different perspectives into account, by setting universal requirements or providing funding schemes.

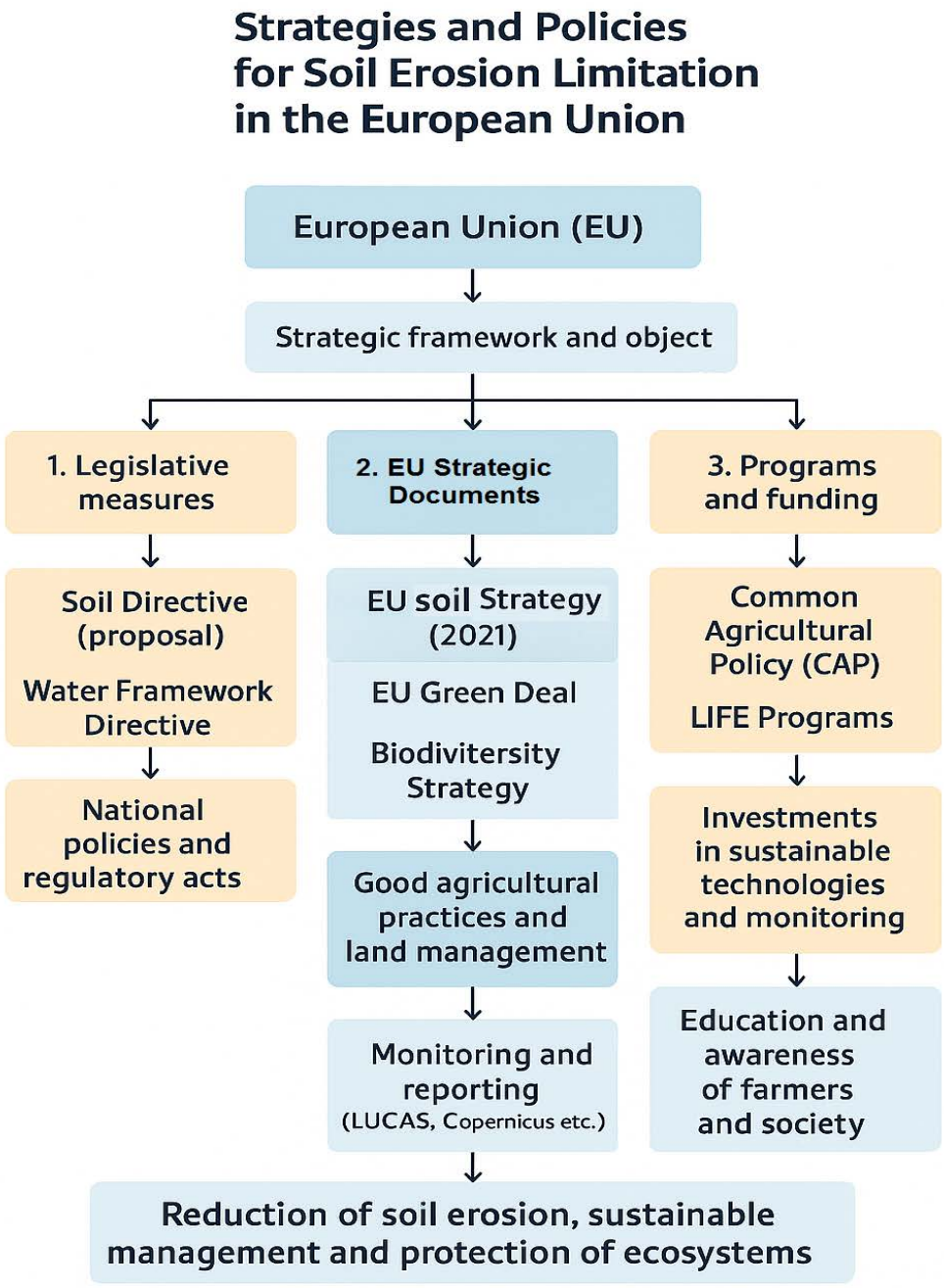
Strategies and Policies for Soil Erosion Limitation in the European Union
European Union (EU)
Strategic framework and object
1. Legislative measures
2. EU Strategic Documents
3. Programs and funding
Soil Directive (proposal)
Water Framework Directive
National policies and regulatory acts
EU soil Strategy (2021)
EU Green Deal
Biodiviersity Strategy
Good agricultural practices and land management
Monitoring and reporting (LUCAS, Copernicus etc.)
Common Agricultural Policy (CAP)
LIFE Programs
Investments in sustainable technologies and monitoring
Education and awareness of farmers and society
Reduction of soil erosion, sustainable management and protection of ecosystems

Fig. 4. *EU strategies for preventing soil erosion.*

Conclusion

Over the past 120 years since the beginning of organized erosion control management in Bulgaria, soil erosion has remained the primary threat to soil degradation. Throughout this period, the state has invested substantial effort and resources in soil protection. Research, technological innovations, policy measures, afforestation, and engineering structures have been employed in erosion control, leading to significant progress; however, much remains to be done. With the growth of the global population and the impacts of climate change, soil erosion is expected to intensify at the global scale, adversely affecting the capacity of soils to produce food and other raw materials. Therefore, continued efforts to control soil erosion are

essential, with a strong emphasis on conservation and regenerative agriculture to safe soils from further degradation.

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Utilizing Soil Quality Index to Inform and Shape Agricultural Sustainability Strategies in Nineveh Governorate, Iraq

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Received: 15 March 2026 *Accepted: 03 May 2026*

Abstract

This research establishes a precision framework for assessing soil quality in the semi-arid regions of northern Nineveh, Iraq, by moving from the traditional Soil Quality Index (SQI) model to the modified soil quality (SQI-plus) model. While traditional soil quality indicators often produce overly optimistic "high quality" classifications, the SQI-plus model reveals the reality on the ground: significant quality degradation, placing most sites in the "medium quality" and "poor quality" classifications. This was achieved through the analysis of 40 geographically referenced sites using 11 physical, chemical, and morphological indicators: organic matter (OM), pH, cation exchange capacity (CEC), calcium carbonate ($CaCO_3$), electrical conductivity (EC), texture, bulk density (BD), effective depth, drainage, slope, and vegetation cover (VC). The study revealed that the decline in soil quality was primarily driven by limited organic matter (affecting 92.5% of sites) and high $CaCO_3$ content (85%), followed by lack of vegetation cover (62.5%) and increased bulk density (60%). The findings conclude that the SQI-plus model provides a symbolic system that identifies the specific factors for each site in arid and semi-arid environments. This work offers a transformative tool for sustainable land management, demonstrating that the resilience of agriculture in northern Iraq depends on addressing chemical and biological constraints rather than physical landscape parameters alone, providing a solid foundation for well-considered agricultural sustainability strategies.

Keywords: Soil Quality Index, agricultural sustainability, organic matter, SQI-plus, limiting factors

Introduction

Agricultural soil is essential for crop production and global food security (Tahat, et al., 2020; Veerman, et al., 2020). It provides 98.8% of our food (Kopittke, et al., 2021), creates the necessary environment for plant growth, and supports vital ecosystem processes (Samaniego, et al., 2025). Furthermore, soil quality is a key factor in determining land productivity, resulting from the interaction between intrinsic soil properties and dynamic

environmental processes, including climate, management practices, and biological activity (Bünemann, et al., 2018; Al-Naser, 2019; Józefowska, et al., 2026). Within this framework, soil quality serves as an integrative assessment approach that defines the capacity of a specific land unit to support particular uses (Freshteh, et al., 2024). The concept of soil quality evolved into an operational framework that can be quantitatively assessed through soil quality indices (SQI) and land evaluation approaches (Rachman, 2020). Within this framework, soil quality reflects the capacity of soil to perform key functions under specific land-use systems and environmental conditions (Qihong, et al., 2025), including sustaining biological productivity, regulating water and air quality, and supporting ecosystem and human health. From an applied perspective, high-quality soils are characterized by their ability to maintain favorable physical conditions and functional stability, even under limiting or harsh climatic environments (Bünemann, et al., 2018). In this context, land suitability assessment provides a complementary decision-support tool by linking measured soil quality indicators with land-use requirements (Doran & Zeiss, 2000; Yahqub, et al., 2024), thereby enabling the identification of optimal management strategies and enhancing the resilience of food production systems (Lehmann & Bossio, 2022).

Soil quality assessment can serve as an indicator for evaluating soil management and land sustainability (AlShoumik, et al., 2024; Destika, et al., 2026) and can also identify productivity problems and inform land management and agricultural systems (Kumari, et al., 2025). For agricultural land, determining its suitability for agricultural production requires a synthesis of a range of physical and chemical factors (Maulood & Darwesh, 2020), as well as socio-economic factors, under a holistic comprehensive structure (Philippot, et al., 2023). Physical properties are determined by several parameters such as soil structure, texture, bulk density, and aggregate stability, which directly affect the hydrological functions of the soil (Pandao, et al., 2024). Chemical properties reflect the soil's ability to provide nutrients and regulate their availability, which depends on indicators such as pH, cation exchange capacity (CEC), nutrient content, and electrical conductivity (EC) (FAO & ITPS, 2020; Samaniego, et al., 2025). Soil organic carbon (SOC) stands out as one of the most important indicators, as it is a major enhancer of physical properties (such as aggregate stability and moisture retention), chemical properties (such as CEC), and biological properties (as an energy source for living organisms) (Delgado-Baquerizo, et al., 2020). Soil indicators are important tools for determining soil quality; therefore, they are selected based on their relevance to soil functions and how they affect local ecosystem services (Wang, et al., 2026). An indicator should be able to describe changes in the soil resulting from management practices (Bünemann, et al., 2018). Because land degradation occurs gradually, reflecting land management practices, if the indicator is not sensitive enough, there is a possibility that harmful changes to soil health will occur without being noticed through the study of these indicators (Paz-Ferreiro & Fu 2016; Adhikari, et al., 2025). This underscores the need for an integrated assessment of soil properties based on sensitive, impactful, and measurable indicators (Metwaly, et al., 2024).

The objective of this research isto provide an integrated vision of soil quality that contributes to enhancing conservation efforts and sustainable management of this strategic non-renewable resource.

Materials and Methods

Study Locations

This study included 40 sites from various areas of northern Nineveh Governorate within the districts of Rabia, Zummar, Sheikhan, Wana, Alqush, Faida, Bashiqa, and Telkaif (AlJawwady, 2019; AlSayegh, 2020; AlAskari, 2022; Younus, 2023; Alhamadani, 2024) (Figure 1). The longitude, latitude, and elevation coordinates (ASL) were recorded for all study sites based on the Global Positioning System (GPS) using a German-made (German eTrax 20) device (Table 1).

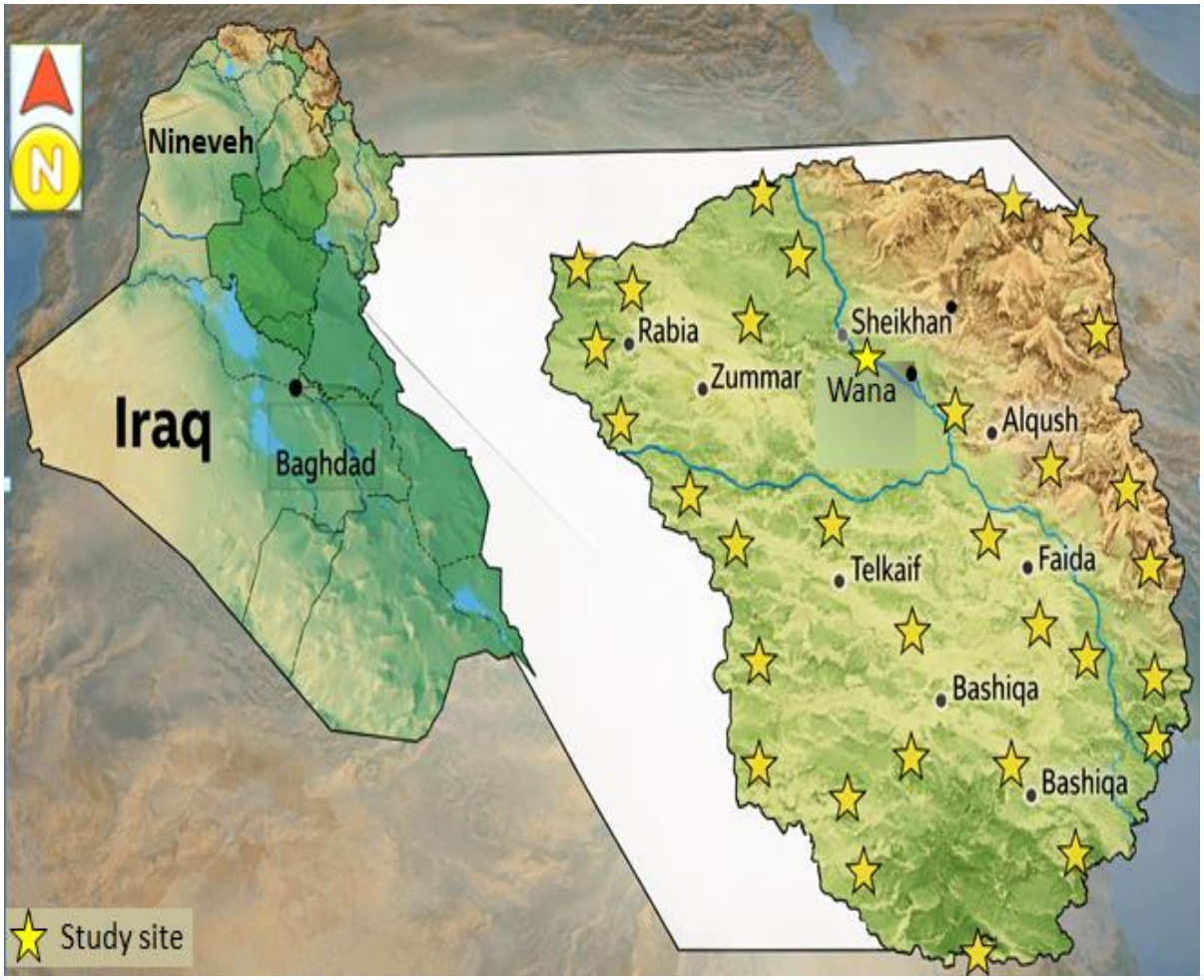

Figure 1. *Study sites in northern Nineveh Governorate within Iraq*

Table 1. *Selected sites within the study area and their GPS coordinates*

No.	Locations	E	N	ASL (m)	Land use
1	Mafri	43°33′07″	36°36′01″	330	Wheat & barely
2	Krkafr	43°31′05″	36°41′11″	345	Wheat & barely
3	Abowjna	43°38′33″	36°41′23″	387	vegetable crops
4	Gheshea	42°39′23″	36°36′58″	366	Wheat & barely
5	Shekan	42°21′38″	36°52′12″	380	Wheat & barely
6	Bardia	42°29′37″	36°47′47″	360	Wheat & barely
7	Sahela	42°20′20″	37°00′36″	453	Wheat & barely
8	Hdayma	42°29'00"	36°31'55"	320	Wheat & barely
9	Telaskf	43°08′53″	36°34′38″	354	Wheat & barely
10	Bahadra	43°14′29″	36°43′44″	545	Wheat & barely
11	Uwaynah	42°59′46″	36°26′29″	292	vegetable crops
12	Amarbet	42°56′11″	36°31′37″	296	Wheat & barely
13	Gambur	42°58′26″	36°43′23″	403	Wheat & barely
14	Shalalat	43°11′27″	36°27′18″	270	Eucalyptus
15	Fadlya	43°15′45″	36°30′20″	326	Olive
16	Mahad	43°25′14″	36°39′10″	418	Wheat & barely
17	Muskan	43°25′01″	36°36′42″	349	Peach
18	Abdlya	43°26′55″	36°27′55″	350	Wheat & barely
19	Besan	43°07′06″	36°27′58″	262	Wheat & barely
20	Batana	43°07′23″	36°33′29″	322	Wheat & barely
21	Derka	43°13′09″	36°29′16″	295	Wheat & barely
22	Barema	43°13′38″	36°32′19″	348	Wheat & barely
23	OrtKhrab	43°15′24″	36°23′57″	257	Wheat & barely
24	Drawesh	43°16′19″	36°25′53″	285	Wheat & barely
25	Basheqa	43°18′10″	36°27′31″	333	Wheat & barely
26	Dbshea	42°27'20"	36°41'10"	353	Vegetable crops
27	Msherfa	42°03'15"	36°45'31"	391	Wheat & barely
28	TelHawa	41°58'49"	36°36'26"	307	vegetable crops
29	Mome	42°02'52"	36°37'38"	405	Wheat & barely
30	Botha	42°15'50"	36°43'01"	392	vegetable crops
31	Mthaltha	42°17'53"	36°37'58"	404	Wheat & barely
32	Gelbarat	42°07'58"	36°49'42"	404	Vegetable crops
33	Mosuldum	42°52'12"	36°36'29"	392	Pastures
34	Wana	42°45'05"	36°31'20"	251	Vegetable crops
35	Telkef	43°06′34″	36°27′34″	257	Wheat & barely
36	Alqush	43°05′30″	36°42′19″	461	Wheat & barely
37	Quba	43°02′45″	36°24′07″	215	Vegetable crops
38	Manara	42°56′50″	36°35′52″	330	Wheat & barely
39	Gambor	43°01′07″	36°42′03″	388	Wheat & barely
40	Sharia	42°59′06″	36°46′28″	650	Wheat & barely

Surface soil samples were collected from a depth of 0–20 cm, air-dried, and sieved through a 2 mm sieve. Soil pH and electrical conductivity (EC) were measured in a soil:water suspension using standard electrodes. Soil organic carbon (OM) was determined by the Walkley–Black method, while calcium carbonate ($CaCO_3$) content was determined using the titration method. Soil texture was determined using the hydrometer method. Bulk density (BD) was measured using the core method, and cation exchange capacity (CEC) was determined using the ammonium acetate method at pH 7. All analyses were conducted

according to standard procedures as described in Page et al., (1982) methods of soil analysis. The results of these analyses are presented in Table 2.

Table 2. *Physical, chemical and morphological properties used in the study*

No.	pH	EC (dS m^{-})	OM	$CaCO_3$	Texture	BD (Mg m^{-3})	CEC ($cmol_c$ kg^{-1})	Slope (%)	Drainage	ED (cm)	VC (%)
			(g kg^{-1})								
1	7.2	1.81	16.6	110.0	ClL	1.40	39.45	3–4	W	100	20-25
2	7.2	0.70	13.8	345.0	Cl	1.32	16.50	2–3	W	100	20-25
3	7.3	0.36	19.0	265.0	LCl	1.26	21.36	1–2	W	100	>75
4	7.5	0.27	15.0	425.0	Cl	1,33	15.00	3-4	W	85	20-25
5	7.5	0.20	17.5	335.0	ClL	1.33	16.40	2–3	W	100	20-25
6	8.1	0.18	17.2	350.0	Cl	1.29	17.00	2–3	W	100	20-25
7	7.5	0.18	21.0	310.0	Cl	1.33	15.00	2–3	W	100	20-25
8	8.0	0.70	10.0	300.0	Cl	1.39	22.76	2–3	W	100	20-25
9	7.8	0.60	17.0	225.0	Cl	1.38	15.90	3-5	W	100	20-25
10	7.9	0.55	18.4	240.0	ClL	1.25	14.00	5-6	W	100	20-25
11	7.7	1.34	16.0	340.0	SClL	1.21	21.70	1-2	W	100	20-25
12	7.0	0.23	10.3	230.0	Cl	1.28	17.00	3-4	W	100	20-25
13	8.0	0.53	15.2	351.0	Cl	1.31	11.00	4-5	W	100	20-25
14	7.8	0.49	18.9	301.0	SiClL	1.31	23.91	2-3	W	100	>75
15	7.8	0.28	15.1	256.0	Cl	1.36	29.89	2-3	W	100	>75
16	7.2	0.26	18.9	104.0	Cl	1.29	35.29	6-7	W	90	20-25
17	7.9	0.33	19.0	292.0	Cl	1.29	32.60	6-7	M	85	>75
18	7.3	0.30	23.4	134.5	Cl	1.27	24.45	8-9	M	75	50-75
19	8.3	0.68	10.5	268.4	ClL	1.21	26.09	2-3	W	100	20-25
20	8.0	0.85	9.3	311.6	SiL	1.31	31.52	5-6	W	90	20-25
21	8.3	0.40	13. 5	302.0	SiL	1.40	22.83	5-6	M	90	20-25
22	8.2	0.52	15.2	340.0	SiL	1.3	26.09	5-6	W	90	20-25
23	8.2	0.43	11.2	236.6	SiL	1.24	21.74	5-6	W	90	20-25
24	8.3	0.43	6.6	273.2	L	1.36	19.57	5-6	W	90	20-25
25	8.3	0.37	7.3	268.4	SiL	1.24	25.00	5-6	W	90	20-25
26	7.8	0.71	19.5	200. 0	L	1.47	25.25	0-1	W	100	>75
27	7.4	2.30	10.3	325.9	SiL	1.32	16.50	0-1	W	100	50-75
28	7.5	1.50	23.1	215.0	SiL	1.33	20.30	0-1	W	100	>75
29	7.5	1.52	23.1	305.0	L	1.70	14.50	0-1	W	100	50-75
30	7.4	2.96	15.2	296.7	L	1.25	16.35	0-1	W	100	>75
31	7.4	0.79	19. 5	175.0	LCl	1.33	10.35	0-1	W	100	50-75
32	7.4	0.71	16.1	297.2	SiClL	1.53	22.50	0-1	W	100	>75
33	7.9	0.50	9.3	310.0	LS	1.32	21.25	7-8	M	75	< 25
34	7.8	1.30	18.6	225.0	L	1.26	24.50	0-1	W	100	>75
35	7.3	0.50	17.0	239.0	Cl	1.35	23.55	2-3	W	100	25-75
36	8.1	0.52	17.6	252.0	LCl	1.21	23.60	6-7	W	100	20-25
37	7.3	3.49	18.0	300.0	Cl	1.28	26.40	0-2	W	100	>75
38	7.0	0.34	13.1	210.0	Cl	1.21	20.55	3-4	W	100	25-75
39	8.0	0.53	15.2	351.0	Cl	1.31	21.30	7-8	W	100	20-25
40	7.9	0.40	18.4	181.4	ClL	1.38	22.30	2-3	W	100	20-25

* ClL: clay loam, Cl: clay, L: loam, LS: loamy sand, SiClL: silty clay loam, LCl: loamy clay, SiL: silty loam, SClL: sandy clay loam, W: well drained, M: medium drained

Soil quality assessment according to SQI and SQI-plus

The SQI-plus classification scheme (0–5 scale) was established by integrating the FAO land evaluation concepts with subsequently developed modifications of soil quality index methodologies, according to the Rachman (2019) methodology, which is based on the Weighted Additive Index method. The calculation process included two main steps:

1- **Selection of indicators:** Eleven attributes were selected to represent the physical, chemical, and morphological functions of the soil: organic matter (OM), pH, cation exchange capacity (CEC), calcium carbonate ($CaCO_3$), electrical conductivity (EC), texture, bulk density (BD), effective depth (ED), drainage, slope, and vegetation cover (VC).

2- Weight allocation and calculation: Based on the Rachman (2019) and Gutierrez)2024 (methodology and relying on the Weighted Additive Index (WAI), relative weights (Wi) were determined for each attribute that reflect its importance in sustainable productivity, with the greatest weight given to OM and ED (Table 3). The data were converted to standard values ranging from 0.1 to 1.0 in the SQI model (Table 4) and from 0 to 5 in the SQI-Plus model (Table 5), using scoring functions based on the principle of "more is better", "less is better", or "optimal", taking into account the calcareous and climatic characteristics of the soils of northern Iraq. The SQI-Plus model is not limited to numbers; it also includes symbols that indicate limiting factors. Letters are added to any criterion scoring 2.00 or lower, classifying these criteria as low and thus considered limiting factors.

Table 3. *Key parameters (Wi) for assessment of Soil Quality Index (SQI)*

Indicator	Wi	Scientific and economic justification
OM	0.15	Driver of fertility and vitality
pH	0.08	Affects the availability of elements
CEC	0.09	Expresses the soil's ability to retain nutrients
EC	0.09	Salinity is an indicator crop selection
$CaCO_3$	0.07	High concentrations affect the physical properties
Texture	0.10	Affects water permeability and nutrient retention
BD	0.07	Indicator of soil compaction and porosity
Depth	0.12	Water and root growth are crucial in agriculture
Drainage	0.05	Essential for root aeration
Slope	0.10	Major factor in soil erosion
VC	0.08	Basic in soil fertility and improved soil structure.
Total	1.00	Sum of the weights must equal one

The value of each attribute (after scored and weighted to a standard value from 0 to 1) is multiplied by its additive method, according to the Standard Weighted Sum Equation (Andrews, et al., 2004):

$SQI = \sum_{i=1}^{n}(Wi \times Si)$

Where: SQI= Final value of the SQI index, Wi= weighting coefficient for each criterion, representing the criterion's significance and impact, Si= score assigned to the criterion based on laboratory or field analysis results, n= number of criteria used.

Table 4. *Criteria used to score each parameter according Andrews et al. (2002)*

Characteristic	Range 1	Score	Range 2	Score	Range 3	Score	Range 4	Score
OM (%)	> 3.0	1.0	2.0– 3.0	0.7	1.0– 2.0	0.4	< 1.0	0.1
Depth (cm)	> 100	1.0	50– 100	0.7	25– 50	0.4	< 25	0.1
EC (dS m^{-1})	< 2.0	1.0	2 – 4	0.8	4 – 8	0.5	8 – 16	0.2
pH	6.5–7.8	1.0	7.8– 8.4	0.7	> 8.4	0.3	—	—
CEC (cmolc kg^{-1})	> 25	1.0	15– 25	0.7	5– 15	0.4	< 5	0.1
Texture	L, SiL	1.0	C, SiC	0.7	S	0.3	—	—
Slope (%)	0 – 2	1.0	2– 8	0.7	8– 15	0.4	> 15	0.1
$CaCO_3$ (%)	< 10	1.0	10– 20	0.7	20– 30	0.4	> 30	0.1
BD (g cm^{-3})	< 1.3	1.0	1.3– 1.5	0.7	1.5– 1.7	0.3	> 1.7	0.1
Drainage	VG	1.0	G	0.8	M	0.5	B	0.1
VC (%)	> 75	1.0	50– 75	0.7	25– 50	0.4	< 25	0.1

Remarks: C= clay; SiL= silty loam; L= loam; SiC= silty clay; S= sand; VG= very good; G= good; M= moderate; B= bad

Table 5. *Criteria used to score each parameter according to Rachman (2019b)*

Parameters	0	1	2	3	4	5
OM %	<0.3	0.3-0.6	0.6-1.0	1.0-1.8	1.8-3.0	> 3.0
depth cm	<10	10-20	20-40	40-60	60-80	> 80
EC (dS m^{-1})	> 8.0	4-8	2-4	1-2	0.5-1	< 0.5
pH	<4.5 or >9.0	4.5-5.5	5.5 -6.5	8.0-8.5	6.5-7.5	7.5-8.0
CEC cmolc kg^{-1}	<5	5-10	10-15	15-25	25-40	> 40
Texture	S	LS	SL	SC, SiC	C, Si	L, SiL, SCL, SiCL, CL
Slope %	>30	20–30	15–20	8–15	3–8	<3
$CaCO_3$ (%)	> 30	30-20	20-15	15-10	10-5	< 1
BD g cm^{-3}	>1.7	1.7-1.5	1.5-1.3	1.3-1.1	1.1-0.9	< 0.9
Drainage	VP	P	SP	M	G	VG
VC (%)	< 10	10–25	25-40	40-60	60-80	> 80

Remarks: C= clay; SiL= silty loam; L= loam; SiC= silty clay; S= sand; Si= silt; SC= sandy, clay; CL= clay loam; SiL= silty loam; SL= sandy loam; SiCL= silty clay loam; SCL= sandy clay loam; LS= loamy sand, VP= very poor, P= poor, SP= slightly poor, M= moderate, G= good, VG= very good

Table 6. *SQI Classification according to Andrews et al, (2002) and Rachman (2019b)*

SQI-plus Score	Classification	SQI Score	Classification
> 0.8	Very High Quality	$x \leq 2.0$	Very bad
0.6-0.8	High Quality	$2.0< x \leq 2.5$	Slightly Bad
0.4-0.6	Moderate	$2.5< x \leq 3.0$	Bad
< 0.4	Low Quality	$3.0< x \leq 3.5$	Medium
		$3.5< x \leq 4.0$	Slightly good
		$4.0< x \leq 4.5$	Good
		$x > 4.5$	Very good

Remarks: x = SQI score

Statistical analyses

All statistical analyses were performed using IBM SPSS Statistics version 16.0 software (SPSS, Inc., Chicago, IL, USA). Descriptive statistics were calculated, and data were screened for outliers and normality prior to further analysis. Soil properties were transformed into standardized scores using predefined scoring functions, and Soil Quality Index (SQI) and SQI-plus values were computed using the WAI approach. Principal Component Analysis (PCA) was applied to identify the most influential indicators and to determine the most suitable model structure. Sensitivity analysis and comparative evaluation between SQI and SQI-plus were conducted, and differences among groups were tested using ANOVA at a significance level of $p \leq 0.05$.

Results and Discussion

1. Methodological comparison: SQI vs. SQI-plus

The assessment of soil quality used in the study reveals a distinct divergence between the traditional SQI and the modified SQI-Plus model in Table 7. Based on the classification criteria in Table 6, most sites were categorized as "High Quality" under the SQI model, with scores ranging from 0.574 to 0.781. When compared SQI-plus with the conventional SQI approach, the application of the SQI-plus methodology-integrating FAO land evaluation principles with a weighted additive index-resulted in a redistribution of sites toward the Medium, Slightly good, and Bad classes. Specifically, SQI-plus classified 13 sites as Slightly good, 15 as Medium, and only two as Bad, indicating a more differentiated assessment of soil quality. This shift highlights the superior sensitivity of SQI-plus in capturing the influence of key soil attributes and demonstrates its enhanced capability to reflect actual soil quality conditions compared with traditional linear SQI models.

2. Analysis of indicator weighting and sensitivity

The research utilized eleven physical, chemical, and morphological indicators, each assigned a weighting coefficient (Wi) based on its scientific and economic justification as shown in Table 3. OM and ED were assigned the highest weights (0.15 and 0.12, respectively), identifying them as the primary drivers of soil fertility and root development in the region. The use of these weights in the equation
SQI = $\sum_{i=1}^{n}(Wi \times Si)$ ensures that the final index value reflects the relative importance of each property in sustaining productivity. The lower weights assigned to factors like drainage (0.05) suggest that while essential for aeration, they were secondary to the foundational roles of fertility and soil volume in this specific environmental context.

3. Impact of physiochemical and morphological properties on quality scores

Table 7 shows that OM and $CaCO_3$ are the most common and influential factors in the entire study area, accounting for 87.5%, followed by VC at 60% and BD at 18%. The least common determinants are salinity (EC) at 7.5% and CEC at 5%. The results also showed that site number 13 was the most affected, exhibiting five determinants (OM, $CaCO_3$, BD, VC, and CEC), leading to its classification as a "bad" soil. Sites (2, 4, 5, 7, 8, 9, 21, 35, and 40) were each affected by four determinants, most commonly OM, $CaCO_3$, BD, and VC. Site number 18 was the least affected, with only one determinant, OM, being identified.

Table 7. *Results of soil quality assessment using SQI and SQI-plus*

No.	SQ1 Score	Classification	SQ1-plus Score	Classification
1	0.694	High Quality	3.47OM, BD, VC	Medium
2	0.625	High Quality	3.13OM, $CaCO_3$, BD, VC	Medium
3	0.745	High Quality	3.73 OM, $CaCO_3$	Slightly good
4	0.598	Moderate	2.99 OM, $CaCO_3$, BD, VC	Bad
5	0.625	High Quality	3.13 OM, $CaCO_3$, BD, VC	Medium
6	0.622	High Quality	3.11 OM,$CaCO_3$, VC	Medium
7	0.643	High Quality	3.22 OM, $CaCO_3$, BD, VC	Medium
8	0.622	High Quality	3.11 OM, $CaCO_3$, BD, VC	Medium
9	0.622	High Quality	3.11 OM, $CaCO_3$, BD, VC	Medium
10	0.616	High Quality	3.08 OM, $CaCO_3$, CEC, VC	Medium
11	0.646	High Quality	3.23 OM, $CaCO_3$, VC	Medium
12	0.667	High Quality	3.34 OM, $CaCO_3$, VC	Medium
13	0.574	Moderate	2.87 OM, $CaCO_3$, BD, VC,CEC	Bad
14	0.703	High Quality	3.52 OM, $CaCO_3$, BD	Slightly good
15	0.721	High Quality	3.61 OM, $CaCO_3$, BD	Slightly good
16	0.715	High Quality	3.58 OM, VC	Slightly good
17	0.693	High Quality	3.47 $CaCO_3$	Medium
18	0.702	High Quality	3.51OM	Slightly good
19	0.670	High Quality	3.35 OM, $CaCO_3$, VC	Medium
20	0.658	High Quality	3.29 OM, $CaCO_3$, BD, VC	Medium
21	0.606	High Quality	3.03 OM, $CaCO_3$, BD, VC	Medium
22	0.673	High Quality	3.37 OM, $CaCO_3$, VC	Medium
23	0.652	High Quality	3.26 OM, $CaCO_3$, VC	Medium
24	0.673	High Quality	3.37 OM, $CaCO_3$, BD, VC	Medium
25	0.778	High Quality	3.89 OM, $CaCO_3$, BD, VC	Slightly good
26	0.697	High Quality	3.49 OM, $CaCO_3$, BD	Medium
27	0.778	High Quality	3.89 EC, $CaCO_3$	Slightly good
28	0.699	High Quality	3.50 $CaCO_3$	Medium
29	0.763	High Quality	3.82 OM, $CaCO_3$, BD	Slightly good
30	0.724	High Quality	3.62 OM, EC, $CaCO_3$	Slightly good
31	0.747	High Quality	3.74 OM, $CaCO_3$, BD	Slightly good
32	0.606	High Quality	3.03 OM,$CaCO_3$, BD	Medium
33	0.772	High Quality	3.86 OM, $CaCO_3$, BD, VC	Slightly good
34	0.691	High Quality	3.46 OM, $CaCO_3$	Medium
35	0.694	High Quality	3.47 OM,$CaCO_3$, BD, VC	Medium
36	0.781	High Quality	3.91 OM, $CaCO_3$, VC	Slightly good
37	0.712	High Quality	3.56 OM, EC, $CaCO_3$	Slightly good
38	0.643	High Quality	3.22 OM, $CaCO_3$, VC	Medium
39	0.643	High Quality	3.22 OM, $CaCO_3$, VC	Medium
40	0.694	High Quality	3.47 OM, $CaCO_3$, BD, VC	Medium

Soil quality assessment based on SQI-plus evaluation

The results shown in Table 7, along with the radar-based frequency analysis (Figure 2), reveal a consistent pattern explaining the spatial decline in Soil Quality Index-plus (SQI-plus) values across the study sites. The decline in SQI-plus was primarily associated with the prevalence of reduced OM, recorded in 37 sites (92.5%), and increased $CaCO_3$ content, observed in 34 sites (85%). The widespread prevalence of these two factors, affecting more

than 85% of the studied sites, indicates that OM depletion and carbonate accumulation are the main drivers of soil quality degradation in the region. Reduced VC and increased bulk density (BD) showed moderate frequencies, affecting 62.5% and 60% of the sites, respectively, suggesting they are less specific in exacerbating soil function degradation than OM and $CaCO_3$. In contrast, EC and CEC were determined at less than 10% of sites, explaining their minimal contribution to Soil Quality Index-plus (SQI-plus) values across sites. This distribution pattern, taken together, suggests that the low SQI-plus values primarily reflect the deterioration of soil chemical and biological properties, particularly under arid and semi-arid environmental conditions. These findings are consistent with the conclusions of Kiani et al. (2017).

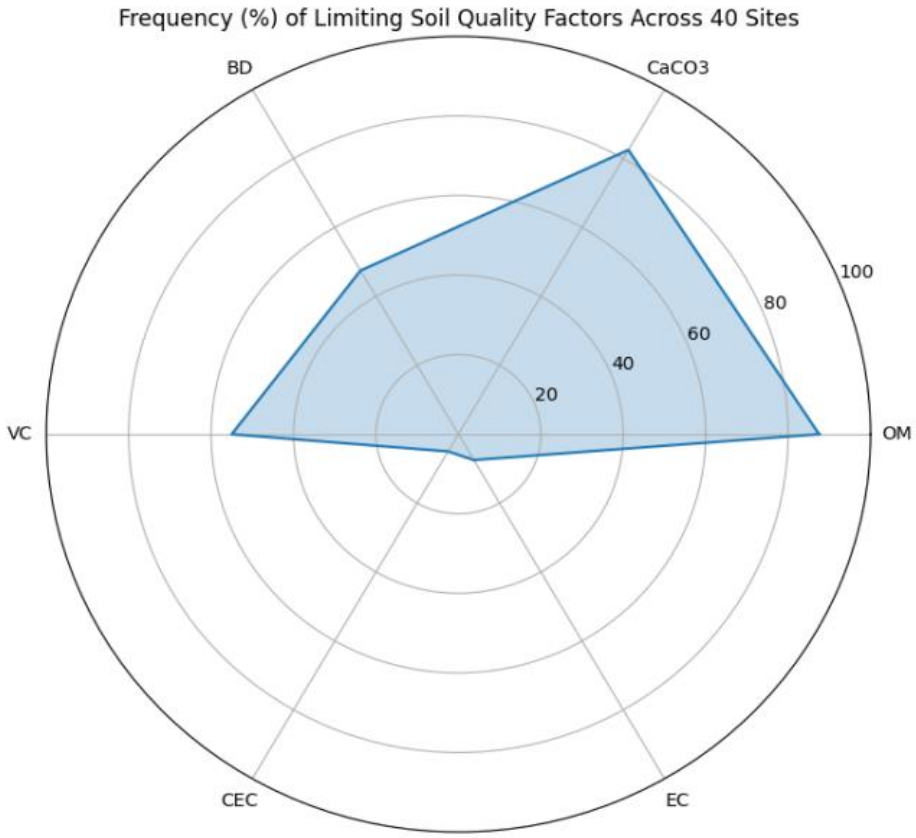

Figure 2. *Radar chart showing the percentage frequency of limiting soil quality indicators across the forty sampling sites based on SQI-Plus analysis*

To further define the balance between soil indicators, the radar polygon area (RPA) for each site was calculated and statistically correlated with the Soil Quality Index (SQI-Plus) results (Figure 3). The analysis showed a strong positive correlation ($r = 0.92$, $p < 0.0001$), confirming that increasing polygon area is directly proportional to improved soil quality. Sites classified as "fairly good" exhibited larger and more balanced radar polygons, while sites classified as "average" and "poor" showed shrunken and irregular polygons, reflecting selective constraints on the indicators.

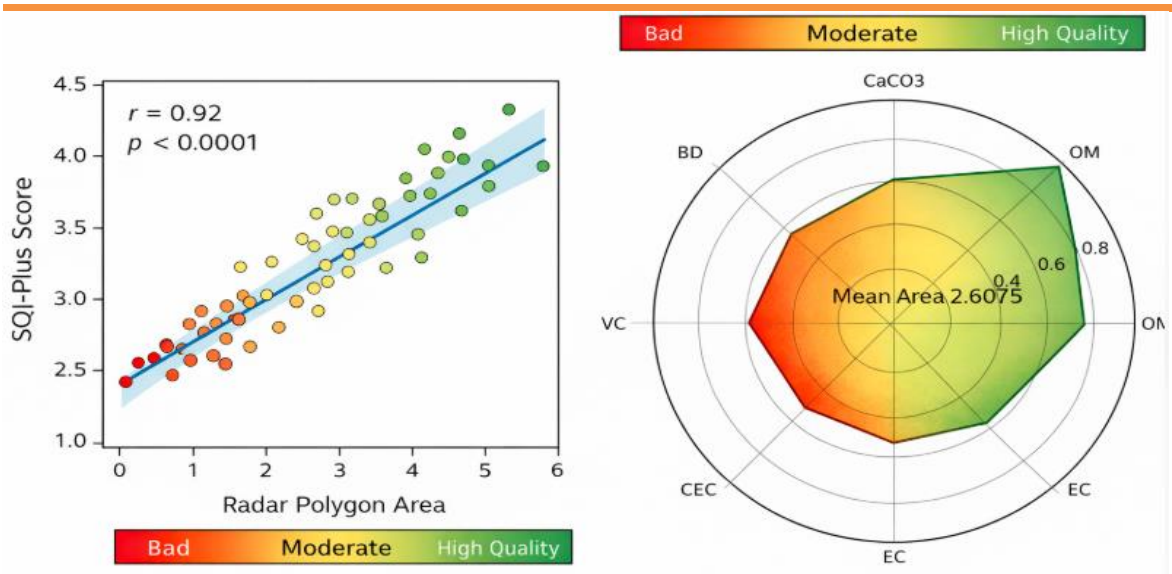

Figure 3. *Positive correlation between radar polygon area and Soil Quality Index (SQI-Plus) scores across the 40 sampling sites. Pearson's correlation coefficient (r = 0.92, p < 0.0001) indicating positive relationship between radar polygon area and SQI-Plus scores*

The predominance of OM and $CaCO_3$ as limiting factors indicates the need to prioritize OM enhancement and carbonate-related soil structure improvement in soil rehabilitation strategies. The limited effect of electrical conductivity also suggests that salinity is not a limiting factor for soil degradation in the studied area.

The linear relationship between RPA and Soil Quality Index (SQI-Plus) was assessed using Pearson's correlation coefficient. The analysis showed an r = 0.92 and a p < 0.0001, indicating a very strong positive linear relationship between the radar-derived geometric equilibrium and the composite soil quality.

Table 8. *ANOVA Table*

Source	df	SS	MS	F	p-value
Regression	1	6.82	6.82	219.4	<0.0001
Residual	38	1.18	0.031	—	—
Total	39	8.00	—	—	—

Statistical Interpretation

The results of the analysis of variance (ANOVA) confirmed that the linear regression model was statistically significant [F(1,38) = 219.4, p < 0.0001], explaining 85% of the variance in the Soil Quality Index (SQI-Plus) scores (R^2 = 0.85). The high F-value and very low mean squared residuals indicate that the radar polygon area is a highly reliable indicator of integrated soil quality performance at the 40 sampling sites.

Conclusion

The results demonstrated that the SQI-Plus model exhibits greater sensitivity than the conventional SQI model in assessing soil quality, as it reclassified sites previously categorized as "High Quality" into more realistic classes such as "Medium" and "Bad," with strong statistical reliability (R^2= 0.92). Soil quality in northern Iraq was found to be primarily constrained by biological and chemical factors rather than physical ones, particularly low organic matter (92.5%) and high calcium carbonate (85%), while poor vegetation cover and high bulk density contributed to degradation in over 60% of sites, highlighting the vulnerability of soil structure and fertility under arid and semi-arid conditions. Organic matter

(0.15) and effective depth (0.12) emerged as the most influential weighted indicators for sustaining productivity, while Site 13 was identified as the most degraded due to multiple limiting factors, resulting in its classification as "Bad."

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Effect Of Solid Piggery Sludge Application on Soil Properties, Cowpea Production, and Tissue Accumulation of Metals under Humid Tropical Lowland Conditions in Papua New Guinea

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Received: 10 March 2026 *Accepted: 3 May 2026*

Abstract

The production of solid piggery sludge (SPS) in Papua New Guinea (PNG) has increased, and there is a need to manage it to avoid environmental concerns. In this study, we investigated the potential use of SPS in cowpea production as a legume to enhance soil health and as a raw material for livestock feed and human food. A replicated field trial with four rates of amendments (0, 2.5, 5.0, and 10 t ha^{-1}) as treatments was conducted under field conditions by planting cowpea. Each treatment was replicated five times (n=5) and set up in a completely randomized block design. After six months of production, the whole plants were uprooted, and the total number of plants and root nodules were counted; and plant height, leaf length, and root length were measured. At the same time, 3 kg of soil samples were collected from the spots where the plants were harvested and packed. All the samples were taken to the laboratory and processed for minerals (nutrients and metals) analysis. The whole plants were oven-dried for dry matter, and leaf and root weights. The averages of all the parameters were obtained by taking the mean of the replicates (n=4). Significant differences ($p<0.05$) between the treatment means were compared by two-way ANOVA, and if interaction between the treatments and profile depth was found, one-way ANOVA with all combinations was performed using Tukey's HSD (honestly significant difference) and pairwise comparisons. The overall results showed that all the soil parameters except pH and texture were significantly improved. At the highest amendment rate, the primary macronutrients N, P, and K were increased by 92%, 133%, and 200%, respectively. The secondary macronutrients and most of the micronutrients were increased significantly as well. The highest dry matter (86%) was produced by the 5.0 t ha^{-1} amendment, and Zn, Mn, Al, Fe, and Cr accumulated in the biomass. Comparatively, Cd, Ni, and Pb in soil and Cd, Cr, Cu, and Pb in biomass were higher than the standard FAO permissible levels of metals. This study showed that agricultural use of SPS has the potential to improve general soil health and increase cowpea production by an amendment rate of 5.0 t ha^{-1} in the humid tropics. A rate of 10 t ha^{-1} was detrimental to cowpea production and to livestock and human beings' health.

Keywords: Bioaccumulation factors, heavy metals, humid tropical lowland, PNG, piggery sludge, soil amendment, soil fertility, *Vigna uniguiculata*.

Introduction

Cowpea (*Vigna unguiculata* L.) is a legume widely cultivated in the tropics because of its socio-economic and nutraceutical importance (Singh et al., 2002) and many other places in the world (Antova et al., 2014). These make cowpea one of the multifunctional crops as food for humans and livestock, income generating commodity for farmers, and a raw material for the industries (Gonçalves et al., 2016; Abebe et al., 2022). On estimation, 5.8 million tons of dry cowpea cereal are produced in 11 million ha of land, with an output of 527 kg ha^{-1} (Xiong et al., 2016). As a legume, cowpea fixes a lot of nitrogen into the soil, e.g., 100 kg ha^{-1} (Rangel and Silva, 2007), and is an excellent substitute for inorganic (chemical) fertilizers for agricultural and environmental sustainability. Inclusion of cowpea, for example, in crop rotation with a non-leguminous crop increases organic matter and improves soil fertility (nutrients), water infiltration and retention, soil microbial activity, and other soil parameters such as pH, electrical conductivity, bulk density, total porosity, cation exchange capacity, and base saturation (Michael, 2019a; 2021). Cowpea is highly stable and tolerant to environmental stresses (drought, salinity, high temperature) and has wider adaptability, making it one of the most widely cultivated legumes in the world (Langyintuo et al., 2003; Guerra et al., 2017).

In developing countries like PNG, where the supply of sources of a balanced diet is low, edible legumes such as peas (*Pisium sativum* L.), peanuts (*Arachis hypogea* L.), beans (*Phaseolus* spp.), and cowpea are an important source of food and nutritional security. Even in the developed countries, cowpea is an important and alternative source of protein as well as other nutritional requirements, low in fat and high in edible fibre, contributing to the health and well-being of the consumers (Timko et al., 2008). As a food source, the mature beans, green pods, and leaves are used as food and as ingredients in the food industries (Frota et al., 2008; Xu and Chang, 2012; Kapravelou et al., 2015; Bello et al., 2017). In terms of human and livestock diet, cowpea is a chief source of carbohydrates, protein, and fats as primary nutrients (energy), minerals, vitamins, and fibre as micronutrients and bioactive compounds (Giami, 2005). Several studies showed cowpea is nutritionally high in macronutrients in protein (e.g., Carvalho et al., 2012; Boye et al., 2012; Santos et al., 2013), carbohydrate (e.g., Phillips et al., 2003; Williams et al., 2008; Vasconcelos et al., 2010), and lipids (e.g., Asare et al., 2013; Antova et al., 2014). In terms of micronutrients, cowpea is an essential source of all the seventeen minerals and thirteen vitamins required to prevent malnutrition and nutritional disorders (DellaPenna, 1999). Nutraceutical compounds are components of food that contribute to critical physiological functions in human and livestock health and range from dietary fibre, probiotics, prebiotics, polyunsaturated fatty acids, antioxidant vitamins, and phenolic compounds. All of these nutraceutical compounds have been reported in cowpea in a range of concentrations (e.g., Das et al., 2012).

Uses of cowpea in management of degraded agricultural land by symbiotic nitrogen fixation potential (e.g., Ruiz-de-Cenzano et al., 2015; Mganga et al., 2016) important for management of soil nutrients and ecological stability are well document. In large-scale production, especially in poor soil, the nutrient requirements of cowpea range from 20 – 25 kg ha^{-1} N, 40 – 50 P kg ha^{-1}, and 20 – 25 kg ha^{-1} (primary macronutrients) and micronutrients such as zinc, iron, and boron. In principle, these nutrient requirements are met through application of inorganic (chemical fertilizers) or organic amendments. In the developing and underdeveloped economies, the availability of inorganic fertilizers is limited to certain places

(towns and cities), and affordability continues to be an issue for small farmers because the costs are often high, making yield to be low and unpredictable (Bakshi et al., 2025). We have shown in several studies that the use of organic matter as soil amendment under various land use conditions is an important option (e.g., Michael, 2019b). Organic amendments provide humus for soil structure stability, drainage, aeration, water holding capacity, mineral solubility, and are an essential energy substrate for soil microbes (Christina et al., 2024). In addition, there is a consensus that organic amendment lowers the cultivation costs and lessen the environmental impacts of chemical fertilizers (Debbarma et al., 2020; Owade et al., 2020; Abebe et al., 2022; Simon et al., 2025).

The different sources of organic amendments include green manure, vermicompost, oil cake, farmyard manure (several in the form of cattle, poultry, goat, sheep, slaughter house trash, crop stumbles and harvesting trashes and so on), and wastes in the form of effluents from processing plants (e.g., oil palm mills) and farm wastes stabilisation ponds (e.g. piggery effluent ponds). These different sources of organic amendments have different soil conditioning properties and application potentials under cowpea production, yet there are limited studies for wider publicity.

Wang et al. (2025) reported that the application of organic fertilizer improved soil physiochemical properties, microbial community structure, and yield of cowpea. The yield of cowpea was increased when grown in soil amended with organic matter (Wang et al., 2025), and similar results were obtained by Darsiah et al. (2021) in soil amended with manure. Subedi et al. (2022) reported high cowpea yield (8.44 t ha^{-1}) in soil amended with poultry manure compared to goat and farmyard manure. Adeoye et al. (2011) stated that poultry and cattle manure use as soil amendment gave similar cowpea yield, just as the finding of Ogunkunle et al. (2023), who found increased and improved general plant growth of cowpea under poultry manure application.

An increasing number of research findings available in the public domain (e.g., Randall et al., 2006; Kyei-Boahen et al., 2017) show that addition of organic matter sources of plant and animal origin improves soil biological, chemical and physical properties and enhances the general growth and development of cowpea (e.g., Olusegun, 2014; Bada et al., 2015; Deepa et al., 2016; Gonçalves et al., 2016; Yogananda et al., 2019; Mfeka et al., 2019; Issoufa et al., 2020; Emmanuel et al., 2020; Osipitan et al., 2021; Sánchez-Navarro et al., 2021; Diatta et al., 2024; Bondok et al., 2024; Bala et al., 2024; da Costa et al., 2024; Ferreira et al., 2025). One other important source of organic matter that received little attention is the use of SPS as soil amendment and cowpea production although there are evidences of findings of studies using pig manure under cowpea production (Olusegun, 2014; Ojo et al., 2020; Atugwu et al., 2023). This study was conducted to investigate the effects of SPS as an amendment on soil properties under cowpea production in the lowland tropical humid tropics and potential tissue accumulation from a general use perspective.

Materials and Methods

Description of study land

The study was conducted at PNGUoT Agriculture Farm (6°41” S, 146°98” E) in Lae, Morobe Province, PNG, at 65 m elevation, described in many publications (e.g., Michael, 2019a; b; 2020a; b; c; d). The climate has 3800 mm annual rainfall, evenly spread, with mean

temperature of 26.3°C, min 22.9°C, max 29.7°C. Evaporation is 2139 mm annually, with rainfall exceeding evaporation each month. Climate is Af (Koppen), a tropical rainy climate with >60 mm driest month. The soil is well-drained, sandy, alluvial, classified as Typic Tropofluents or Eutric Fluvisol. Selected soil parameters, nutrients, and metal contents of the site are given in Table 1.

Table 1. *Soil parameters of the farm soil, SPS and expected range in the amended soils.*

Soil parameters	Composition of parameters of the farm soil and the SPS		
	Farm (study site)	SPS	Range
Soil organic matter (SOM, %)	2.59±0.1	22.17±0.1	3 – 22
Soil organic carbon (SOC, %)	1.50±0.0	12.76±0.8	2 – 13
pH	6.50±0.1	6.80±0.6	6 – 7
Cation exchange capacity (meq/100 g)	7.23	–	–
Base saturation (BS, %)	65.30±0.5	11.76±0.2	6.5 – 12
Electrical conductivity (EC, mS m^{-1})	0.03±0.1	1.92±1.2	0 – 2
Water holding capacity (WHC, %)	54.25±1.0	53.71±0.6	54 – 54
Bulk density (BD, g cm^{-3})	1.12±0.0	0.60±0.1	0.6 – 1
Total porosity (TP, %)	52.02±0.6	56.02±1.2	52 – 56
Particle composition (SPC, %)			
(a) Sand	89.982±0.0	83.13±0.0	83 – 90
(b) Silt	0.45±0.0	4.01±0.1	0.5 – 4
(c) Clay	9.63±0.0	12.83±0.0	10 – 13
N (mg kg^{-1})	1500±0.2	17,600±20.3	15,000 – 18, 000
P (mg kg^{-1})	10.62±0.3	49.62±1.1	11 – 50
K (mg kg^{-1})	20.73±0.3	145.94±4.9	21 – 146
Mg (mg kg^{-1})	131.28±5.7	666.02±10.6	131 – 670
Ca (mg kg^{-1})	732.11±5.6	2,643.27±54.5	732 – 2,640
S (mg kg^{-1})	6.52±0.7	144.24±0.8	7 – 144
Na (mg kg^{-1})	14.32±0.5	62.72±2.3	14 – 63
Fe (mg kg^{-1})	507.38±0.2	72.89±0.50.2	73 – 507
B (mg kg^{-1})	8.82±0.8	18.01±0.9	9 – 18
Mn (mg kg^{-1})	46.30±0.6	191.17±0.5	46 – 191
Al (mg kg^{-1})	270.67±1.1	9.23±1.3	9 – 271
Cd (mg kg^{-1})	6.62±0.2*	12.67±0.3*	7 – 13
Ni (mg kg^{-1})	70.61±0.8*	43.73±0.7	44 – 71
Pb (mg kg^{-1})	730.56±1.3*	4.43±0.2	4 – 731
Zn (mg kg^{-1})	89.56±1.1	439.14±1.5	90 – 439
Cr (mg kg^{-1})	96.08±0.1	21.19±0.7	21 – 96
Co (mg kg^{-1})	<5.12±0.0	<5.21±0.0	<5
Cu (mg kg^{-1})	257.82±2.3*	65.09±0.2	65 – 258

The values are means of three replicate samples ± standard error. Note, range is the expected change in the amended soils. An asterisk shows concentrations higher than FAO permissible limits of agricultural soil, however, the farm is within a residential area and the concentrations maybe considered permissible.

Collection and preparation of piggery sludge

Solid treated piggery sludge was collected from a stockpile from a commercial piggery farm outside of Lae City and brought to the farm for use. The samples were dried on canvas under direct sunlight for a week and weighed using an electric scale. The dried sludge samples were packed into 1000 g, 500 g, and 250 g polyester bags and kept dry before field applications. An analysis of soil parameters, nutrients, and metal contents of the SPS is shown in Table 1.

Sourcing of planting materials

Cowpea (*V. unguiculata*) was chosen as the target plant and planted as it is essential for various industries as raw materials for feed production for livestock, as well as food for human consumption in PNG. The seeds were sourced from local suppliers within Lae City, Morobe Province, PNG.

Land preparation and setting of experiment

A piece of land (17 m x 13 m; 221 m^2) on the farm was ploughed and harrowed using a tractor (Messy Ferguson, Germany). A total of 96 experimental plots (1 m x 1 m) were prepared, separated by a 0.5 m spacing within and between plots. There were four treatments: control (planted with no amendment), 2.5 (lowest), 5 (high), and 10 (highest) t ha^{-1} of SPS. All the treatments were replicated five times (n=5) and arranged in a randomized complete block design (RCBD). The SPS was applied to the soil surface and manually incorporated using handheld shovels into the top 30 cm.

Planting and production management

Based on germination test results, fifteen seeds of cowpea were sown. Throughout the four months of running the study, watering, weeding, and pest and disease control were carried out as per the farm's general practice. There was no thinning done to the plants.

Field Sampling and preparations

Sampling and yield related parameter assessment

All the biomasses (above and below ground) sampled from all the treatment plots. Soil and root samples were collected from the top 30 cm rhizosphere or a 10 cm radius of the plants. Each plant was gently uprooted with minimum root disturbance using a handheld shovel. The soil with the intact roots was carefully shaken onto a canvas and homogenized by mixing before collecting 3 kg of soil subsample per replicate or 12 kg per treatment, and bagged into pre-labelled paper bags. The shoot and root biomasses were chopped into 1–2 cm long pieces using a gardener’s clipper and bagged in pre-labelled plastic bags. All the samples were transported to the laboratory for further processing (cleaning, washing, and oven-drying).

Sample preparations

At the laboratory, the roots were gently washed under tap water to remove excess soil, and the fresh weight was taken. Then the samples were air-dried at room temperature for 24 hours, and all the leaves, stems, vines, and roots were chopped into 1-2 cm long pieces using kitchen knives, packed into paper bags, and oven-dried at 65 °C for three days to determine dry matter (yields). The dry samples were then ground using a food blender, packed into resealable bags, and kept dry to analyse the mineral content. The soil samples from the field were transferred to aluminium trays and air-dried at room temperature for 7 days, and then

sieved into 0.05 mm, 0.5 mm, and 2.0 mm for different measurements and analyses at the PNGUoT Analytica Laboratory.

Laboratory analysis of parameters

Important soil physical and chemical properties that influence soil fertility, mineral, and nutrient availability were determined according to Michael (2020a; b; c; d). Ground biomasses were analysed using laboratory analytical equipment, and the standard equations (Eqn. 1 to 10) were used to assess. Total nitrogen was analysed by the Kjeldahl method (Buchi K436 speed digester and Buchi K-350 Kjeldahl distillation unit). A sample of one-gram (< 2 mm) air-dried soil was digested using 15 ml of concentrated sulfuric acid at 300 – 400 $^{\circ}$C (H_2SO_4 reduces nitrogen as ammonium sulphate $(NH_4)_2SO_4$). The sample solution was distilled using 60% sodium hydroxide (NaOH), where ammonium (NH_4^+) was converted to ammonia (NH_3) gas, which was collected using 25 ml of 2% boric acid with three drops of mixed indicator. It was then back-titrated with 0.01 M HCl. The available nitrogen (NO_3^-N) was determined using the salicylic acid method with UV light after extraction with 0.027 M $Ca(OH)_2$. The available P was determined by Olsen using a spectrophotometer (UV1800, Shimadzu Corporation, Japan) using 0.5 M sodium bicarbonate ($NaHCO_3$) after adjusting the pH to 8.5 with NaOH. Extraction was for 30 minutes using a 200-rpm shaker at a soil-to-extraction solution ratio of 1:20 (w/v).

All the other nutrients (K, Mg, Na, Ca, S, Mn, Zn, B, Cu, Fe, and Al) were extracted with a Melich 3 extraction solution (0.2 M CH_3COOH + 0.25 M NH_4NO_3 + 0.015 M NH_4F + 0.13 M HNO_3 + 0. 001 M EDTA) in 1:10 (soil: extractant ratio) and analysed using an ICP OES. The data was calculated as per Melich3 18F1 standard as follows:

$$N = ((C - B) \times (Ve \div Ws)) \quad (1)$$

Where N is nutrient, e.g., K, C is concentration, B is blank ((mg element/dm^3), Ve is effective volume used in the extraction calculation (1:20 soil to solution), and Ws is the weight of the sample, respectively. The data in milli-equivalent (mEq./100 g soil) were converted to milligrams (mg) as follows:

$$mg = [(mEq \times Aw) \div V)] \quad (2)$$

Where Aw is the atomic weight of an element (e.g., nitrogen) and V is valence, respectively. Cation exchange capacity (CEC) was estimated based on the sum of the individual base cations (Ca, Mg, K and Na) as follows:

$$CEC = \left(\frac{\text{Sum of bases}}{\text{Base saturation \%}} \right) 100 \quad (3)$$

Sum of bases are in meq/100g and are individual exchangeable base cations. Based saturation (%) is from the soil analysis data (e.g., Table 5).

Soil moisture content was determined by oven-drying samples at 105 °C for 24 hours, and the final weight was estimated after 2 hours of cooling by subtracting the dry weight from the initial fresh weight.

The pH was measured using a standard dilution (1:5 soil: water w/v)) method (Michael, 2019b). Electrical conductivity was measured using a Direct Soil EC meter (Spectrum

Technologies Inc., 12360S Industrial Dr. East Plainfeld, IL 60585, USA), using the same solutions (Michael, 2020a; b; c).

The bulk density (g cm^{-3}) was calculated by oven-drying the cores at 105 °C for 48 hours, followed by weighing again (Michael, 2020d). The oven dry weights were divided by the core volume and estimated as follows:

$$BD = (Odw \div \pi r^2 h) \quad (4)$$

Where BD is bulk density (g cm^{-3}), Odw is oven dry weight and formula for estimation of the volume of the core.

The soil organic carbon (SOC) content was analyzed using the weight loss-on-ignition method. A five-gram sample was weighed into a crucible and heated in a muffle furnace for 12 hours at 105 °C (Wf). The weights were recorded after 2 hours of cooling, further combusted at 375 °C for 17 hours (Fw), cooled for 2 hours, and weighed (Michael, 2019a).

The SOC content was estimated by multiplying the carbon value by a conversion factor (1.72) and expressed as a percentage:

$$SOC\ (\%) = [((Wf - Fw) \div Wf) \div 1.724)100] \text{ or } (SOM\ (\%) \div 1.724) \quad (5)$$

The conversion factor was used to convert the soil organic matter content to organic C, assuming there was 58% C in the organic matter.

The size of the C stock in each profile was calculated as the sum of the individual C fractions (%) × BD (g cm^{-3}) × profile depth (SP, cm) x Cf and expressed as a percentage as per Michael (2020) as follows:

$$SOC_{stock}\ (\%) = [((SOC/100) \text{ x } BD \text{ x } SP) \text{ x } Cf] \quad (6)$$

Where SOC was determined using Eqn. 4 and the Cf obtained by 100 ÷58. The soil organic matter (SOM) contents were estimated using the SOC content and the conversion factor as follows:

$$SOM\ (\%) = [(SOC) \text{ x } Cf)] \quad (7)$$

The water holding capacity (WHC) was estimated by soaking soil samples in water (100% WHC) and draining them through filter paper overnight (e.g., Michael, 2019a). These were weighed for the wet weight (W_w), dried in an oven at 105 ˚C for 24 hours, and reweighed to obtain the oven-dry weight (OD_w). The WHC was estimated as follows:

$$WHC\ (\%) = [((W_w - OD_w) \div OD_w)\ 100] \quad (8)$$

The total porosity was determined as follows:

$$P = [(1 - \left(\frac{BD}{d}\right))100] \quad (9)$$

Where P is total porosity (%), BD was defined and d is particle density of 2.65 g cm^{-3}.

The weight of the SOM to a given depth and area was estimated as follows:

$$SOM\ (tons) = [(SOC \text{ x } BD \text{ x } SP \text{ x } ha)\ 1.72] \quad (10)$$

Where SOC is in %, BD is in g cm^{-3}, SP is in m and ha is hectare (10 000 m^2).

The bioaccumulation factors (BiF) were calculated as follows:

$$BiF = \left(\frac{Mpt}{Ms} \right) \quad (11)$$

Where Mpt is metal concentrations of plant tissues and Ms is metal concentration in the soil. Values >1 indicate metal accumulation, whereas values <1 suggest limited uptake or exclusion mechanisms.

Statistical analysis

Data from four replicates of all the treatments were used for statistical analysis and the samples from the fifth replicate were kept frozen as reserves to cater for losses due to mishandling of samples or related issues. The replicated data were used to calculate the treatment means and standard errors. Assumptions of normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test) were tested for each response variable and the data were log-transformed where necessary to meet assumptions.

This was followed by a two-way ANOVA with pasture and amendment rate as fixed factors to test for main effects and interactions. When significant interactions were detected ($p<0.05$), one-way ANOVA with significant treatment effects, and Tukey's HSD post hoc test for pairwise comparisons was used. All analyses were conducted using JMP Pro 16 (SAS Institute Inc., Cary, NC, USA).

Results and Discussion

Changes in soil properties

The SOM contents of the farm soil was within a range (2%) of typical sandy loam soil (Table 1). When the SPS with 22% SOM was added, the content of the amended soils significantly increased, with the highest being measured from the highest rate, the increase being nearly 5.87% (Table 2). That is almost 59 g SOM kg^{-1} soil. In the control soil, 12 g C kg^{-1} soil was measured (Table 2) compared to the 15 g C kg^{-1} in the farm soil (Table 1).

The general trend in the SOC contents was similar to the SOM contents, the changes ranging from 27 g C kg^{-1} to 80 g C kg^{-1} (see Table 4). For example, when the rate of amendment was 2.5 t ha^{-1}, the SOC increase was 15 g C kg^{-1} and it increased to 6.76% by the highest rate (Table 2). SOC is generally 58% of the SOM and is important for various ecological services (e.g., Michael, 2021).

These results showed SPS is important to SOM and SOC contents, as well as the other soil properties. There was not much change in the soil pH, and it remained within a preferable range of 5.5–7.0. Soil moisture and WHC were also improved by higher rates.

Table 2. *Changes in soil properties under bean production.*

Parameters		The different rates of the amendment (t ha^{-1})			
		0	2.50	5.00	10.00
SOM (%)		2.05±0.1^{a}	3.82±0.6^{a}	5.21±0.9^{b}	7.87±0.1^{c}
SOC (%)		1.19±0.0^{a}	2.65±0.1^{b}	4.69±0.1^{c}	7.95±0.6^{d}
pH		6.50±0.6^{a}	6.53±0.9^{a}	6.40±0.0^{a}	6.60±0.0^{a}
Moisture (%)		7.52±0.8^{a}	7.72±0.2^{a}	8.32±0.5^{b}	9.34±0.7^{cb}
WHC (%)		62.15±0.9^{a}	66.83±0.8^{a}	70.13±0.1^{b}	75.63±0.6^{bc}
BS (%)		65.70±0.8^{a}	67.83±0.8^{a}	69.13±0.6^{a}	73.63±0.6^{b}
CEC (meq/100 g)		6.51±1.11^{a}	7.79±0.25^{a}	10.92±1.12^{b}	12.27±2.21^{bc}
EC (mS m^{-1})		150.21±0.5^{a}	160.32±0.0^{b}	175.22±0.2^{c}	186.66±0.0^{dc}
BD (g cm^{-3})		1.21±0.2^{a}	1.13±0.6^{a}	1.12±0.5^{a}	1.11±0.1^{a}
TP (%)		36.02±0.5^{a}	40.22±1.1^{a}	43.23±1.1^{b}	44.44±1.3^{bc}
SPC (%)	Clay	10.99±0.5^{a}	9.87±0.4^{a}	10.01±0.2^{a}	9.86±0.6^{a}
	Silt	2.64±0.3^{a}	0.45±0.5^{b}	0.46±0.2^{bc}	0.46±0.5^{bd}
	Sand	86.37±0.2^{a}	89.68±0.5^{a}	89.53±0.0^{a}	89.68±0.5^{a}

The values are mean ± standard error of four replicates (n=4). The different letters within a row indicate statistical differences at $p<0.05$. The acronyms have been described in Table 1.

The changes measured in BS, EC, BD, TP, and SPC were positively influenced by the higher amendment rates, the most significant changes being induced by 10 t ha^{-1} (Table 2). Notably, TP decreased under the highest amendment rate, and this seems to have been caused by the weight of the amendment rather than the texture (sand, silt, and clay composition). The soil texture remained nearly unchanged, and that was reflected in the soil moisture content. Soil moisture level decreased SPC increased. The general changes in the soil properties measured reflected on the SOM contents, and more so the SOC that is associated with it. Various researchers have pointed out that the improvement in SOC from organic matter, such as the SPS, affects aggregate stability (Bronick and Lal, 2005), cation exchange capacity, nutrient cycling, nitrogen mineralization (Weil and Bradley, 2017), microbial activity with C as a carbon source (Poeplau and Don, 2015; Schloter et al., 2018), and nutrient use efficiency, and yield (Franzluebbers, 2010). Han et al. (2018), for example, showed that an increase in SOC by 0.1% (10 g C kg^{-1}) could lead to 4.0 to 6.6 bushels per acre per year of yield (biomass). In this study, an increase of 8 g C kg^{-1} soil resulted in dry matter production of 51 g, a 59.30% increase compared to the control (biomass data, Table 5).

Changes in soil mineral and metal compositions

The farm soil had a certain level of nutrients, the highest being N (Table 1). Following the amendments, all the primary and secondary macronutrients increased with an increase in rate of amendments (Table 3). Addition of 2.5 t ha^{-1} increased N by 15.39%, 53.85% by 5.00 t ha^{-1}, and by 92.31% by 10 t ha^{-1}. A proportionate increase in all the other primary and secondary macronutrients was measured in all the amended soils. The soil S experienced a steady increase, ranging from 10–52 mg kg^{-1} as well (Table 3). Most of the trace elements (the heavy metals and Al) were significantly high in all the soils amended with high rates. Compared to the contents of the original soil and SPS (Table 1), elements like B, Pb, Ni, Cr, and Co contents were unchanged or decreased. The overall changes in the compositions of

metals, except for Cd, Ni, and Pb, were within the maximum permissible limits of agricultural soils (Table 3). Cd, Ni, and Pb are highly toxic soil pollutants and cause severe environmental damage, including soil degradation, soil quality impairment, and impaired water quality. These metals bioaccumulate in organisms and are potential threats to crops, livestock, and humans through food chains.

Table 3. *Changes in soil mineral and metal compositions under bean production.*

Elements	The different rates of the amendment (t ha^{-1})				Permissible
(mg kg^{-1})	0.0	2.5	5.0	10.0	(FAO/WHO)
N	1300.21±0.1^{a}	1500.11±0.0^{b}	2000.22±0.0^{c}	2500.32±0.1^{d}	
P	8.47±0.1^{a}	10.53±0.1^{a}	13.32±0.1^{ab}	20.46±0.1^{c}	
K	18.08±0.5^{a}	22.27±0.5^{a}	35.21±0.5^{b}	54.44±0.4^{c}	
Ca	610.21±1.4^{a}	734.33±5.0^{b}	1080.01±6.8^{c}	1137.33±7.9^{d}	
Mg	129.84±3.2^{a}	174.33±1.5^{b}	226.00±2.3^{c}	347.33±1.5^{d}	
Na	12.33±1.4^{a}	25.98±1.8^{b}	41.45±1.2^{c}	55.14±1.2^{cd}	
S	4.03±0.2^{a}	14.24±0.2^{b}	34.63±0.2^{c}	56.74±0.2^{d}	
B	6.89±0.9^{a}	11.53±0.9^{a}	13.62±0.8^{ab}	16.21±0.0^{bc}	
Mn	39.33±0.8^{a}	47.87±0.9^{b}	55.76±0.6^{bc}	67.9±0.9^{cd}	
Cu	57.28±0.4^{a}	62.24±0.7^{a}	75.48±0.9^{b}	109.32±0.7^{bc}	36 – 100
Zn	53.11±0.2^{a}	67.44±0.4^{b}	80.03±0.7^{c}	87.93±0.1^{cd}	50 – 300
Fe	410.67±1.5^{a}	449.67±1.5^{a}	468.15±1.1^{ab}	514.52±1.7^{bc}	50,000
Cd*	3.24±0.1^{a}	6.96±0.3^{b}	12.60±0.1^{c}	17.01±0.0^{d}	3.0
Ni*	47.49±1.4^{a}	58.63±0.9^{b}	67.92±1.5^{bc}	91.16±1.3^{d}	35 – 50
Pb*	511.01±1.2^{a}	547.39±0.5^{b}	608.85±1.4^{c}	692.64±1.6^{cd}	85 – 100
Cr	41.77±1.6^{a}	52.77±1.9^{b}	63.48±2.5^{c}	75.02±2.1^{d}	100.0
Co	0.06±0.0^{a}	0.07±0.0^{a}	0.05±0.0^{a}	0.08±0.1^{a}	50.0
Al	133.26±1.1^{a}	140.22±1.2^{a}	152.50±1.4^{b}	161.66±2.0^{bc}	≤30,000

The values are mean ± standard error of four replicates (n=4). The different letters within a row indicate statistical differences at $p<0.05$. An asterisk shows concentrations higher than FAO/WHO permissible limits of agricultural soils.

Some of these minerals, whose concentrations decreased, would mean tissue accumulation and are a concern for the livestock, humans, and the environment (discussed hereunder). For example, the Pb content of the soil was expected to be 730 mg kg^{-1}; however, there was 511 mg kg^{-1} in the unamended soil, and that was increased by 36 mg kg^{-1} when 2.5 t ha^{-1} was added to the soil. The highest amendment rate resulted in an increase of 181 mg kg^{-1} (Table 3), supporting the assumption that the need for Pb is minimal or tissue accumulation. The Al in the control soil (Table 3) was less than what was available in the farm soil (Table 3), but as the amendment rates were higher, there was more in the soil. Overall, the results showed that SPS amendment of soil for cowpea production is important for the macronutrients as well as the trace elements essential to the plants. The heavy metals, Al, and the rest of the trace elements were within the FAO maximum limits of dangerous substances in soil, except Pb, which was higher than 50 mg kg^{-1} (Table 3). The Pb concentration in the soil measured was even higher than the expected residential value of 300 mg kg^{-1} (Flora et al.,

2012; Assi et al., 2016) and therefore is a concern from human beings and livestock health perspectives.

Metal concentrations in biomass

The metal concentrations of the unamended soil were high (Pb>Al>Cu>Fe>Cr>Zn>Ni), and those of the others less than 10 mg kg^{-1} (Table 4). In the 2.5 t ha^{-1} amended soils, all the heavy metal concentrations increased significantly except for Co and Cr, which were not significant (Zn>Cu>Mn>Al>Fe>Pb>the rest). The tissue compositions of 5–10 t ha^{-1} of all the metals generally decreased. The highest decrease in concentrations of the metals depended on the concentrations of the unamended soil and the sludge. The changes in tissue concentrations were the opposite of those of Zn and Mn, which were high throughout. Comparatively, only Cd, Cr, Cu, and Pb concentrations were higher than the maximum permissible limits of crops (Table 4). These metals are highly toxic to plants, thereby inhibiting growth and reducing biomass. As pointed out above, these metals bioaccumulate and are potential threats to livestock and human health.

Table 4. *Metal concentrations in biomass at different rates of amendments*.

Metals	Different rates of amendments (t ha^{-1})				Permissible
(mg kg^{-1})	0.0	2.5	5.00	10.00	(FAO/WHO
Al	151.44±0.4^{a}	128.54±0.3^{b}	124.44±0.6^{ab}	99.33±0.2^{c}	(–)
Cd*	3.52±0.5^{a}	12.55±0.6^{b}	6.53±0.6^{ac}	2.22±0.2^{ad}	0.1 – 0.2
Co	4.32±0.5^{a}	4.11±0.5^{a}	3.99±0.5^{a}	3.89±0.8^{a}	50.0
Cr*	52.23±0.1^{a}	62.99±0.2^{a}	50.11±0.4^{a}	40.24±0.6^{b}	1.3 – 1.5
Cu*	186.24±0.2^{a}	258.66±0.6^{b}	245.54±0.3^{ab}	211.46±0.5^{bc}	73.0
Fe	95.45±0.8^{a}	127.25±0.4^{b}	109.62±0.4^{ac}	63.22±0.2^{ad}	425.0
Ni	18.66±0.4^{a}	39.33±0.4^{b}	35.45±0.7^{bc}	12.29±0.1^{ad}	67.0
Pb*	215.66±0.7^{a}	112.22±0.2^{b}	122.32±0.5^{bc}	39.54±0.2^{d}	0.3 – 2
Zn	34.67±0.4^{a}	455.66±0.1^{b}	439.21±0.6^{bc}	438.21±0.4^{bd}	99.4 – 500
Mn	6.65±0.5^{a}	176.55±0.6^{b}	180.54±0.2^{bc}	167.84±0.2^{bd}	500.0

The values are mean ± standard error of four replicates (n=4). The different letters within a row indicate statistical differences at $p<0.05$. An asterisk shows concentrations higher than FAO/WHO permissible limits of plants (crop). Permissible limit not available (–).

The BiF of the metals per the rates were Al (1.14, 0.89, 0.81, 0.61), Cd (1.09, 1.85, 0.50, 0.13), Co (72.00, 58.81, 0.32, 0.23), Cr (1.25, 1.19, 0.78, 0.54), Cu (3.23, 4.18, 3.24, 1.95), Fe (0.23, 0.28, 0.24, 0.12), Ni (0.40, 0.66, 0.53, 0.13), Pb (0.42, 0.20, 0.20, 0.06), Zn (0.66, 6.81, 5.49, 4.98), and Mn (0.18, 3.71, 3.23, 2.47). These results showed that at the lowest rate, Al, Cd, Co, Cr, and Cu accumulated in the biomass, and there was less uptake of Fe, Ni, Pb, Zn, and Mn (BiF <1). When the rate of amendment was higher, the BiF of all the metals was less than 1 except Cu, Zn, and Mn, indicating uptake was limited to the latter three (Cu, Mn, and Zn), whereas the others were excluded. The data in Table 5 show that there was significant root production in the soil amended with the high SPS rate, and therefore, the BiF being less than 1 is an exclusion mechanism of cowpea, rather than the root becoming a limiting factor for the uptake.

In a study by Srivastava and Chopra (2014), cowpea was planted in soil irrigated with sugar mill effluent at different rates, and heavy metal accumulation in soil and tissues was determined. The results showed Zn, Cu, Ni, Cd, Cr, and Fe concentrations were high in the soil and in the tissues from the soil that received the highest irrigation amounts, agreeing with the data in Table 4. In a three-year study, Silva et al. (2013) repeatedly added tannery sludge compost to the soil and cultivated cowpea at the same rate as ours and a 20 t ha^{-1}. When metal accumulation was determined, only Cr accumulation was significant, and there was no translation to the grains. When the relationship between metals in the soil and in the seed was studied, most of them did not exceed the maximum permissible limit (Ismael et al., 2016) except Pb in the seeds. When the effects of metals (Zn, Fe, Cu, Cr, and Pb) on the growth were studied, Okon et al. (2023) reported that cowpea showed more tolerance compared to its counterpart, groundnut. These studies confirm the findings of our study that cowpea has a certain level of tolerance to metals and therefore lesser tissue accumulation (lower BiF, Table 4). Comparatively, our results further showed that tissue accumulation is dependent on the sources and the amounts of the metals in them. The combined soil and SPS content of metals was Pb>Fe>Zn>Cu>Al>others (Table 1), and some of these were the highest in the tissues.

Plant biomass production

The plant biomass produced (Table 5) reflected the significant changes in soil parameters (Table 2), soil nutrients (Table 3), and concentrations of metals (Table 4) measured. More plants were produced in the soil that received the highest SPS rate, where, in general, the soils were more fertile (high nutrients) with notably high SOM and SOC contents, agreeing with the findings of Lopes et al. (2020). Sewage sludge fertilization and cultivation of cowpea resulted in high vegetative growth and grain yield, and the results were related to improvements in SOM and nutrient mineralization. The tallest plants were from the soils amended with the higher amounts of the SPS, and that directly influenced the other plant growth parameters, leaf number, leaf length, and pod number (Table 5).

Table 5. *Biomass production at different rates of amendments.*

Plant parameters	Different rates of amendments (t ha^{-1})			
	0.00	2.5	5.00	10.00
Plants (number)	20.22 ± 0.5^{a}	29.12 ± 0.4^{a}	40.44 ± 0.5^{b}	58.23 ± 0.5^{c}
Height (cm)	148.33 ± 0.2^{a}	198.24 ± 0.2^{b}	224.67 ± 0.6^{c}	299.33 ± 0.5^{cd}
Leaf (weight, g)	42.23 ± 0.0^{a}	58.25 ± 0.2^{b}	60.33 ± 0.2^{bc}	75.33 ± 0.1^{d}
Leaf length (cm)	1.66 ± 0.5^{a}	2.23 ± 0.3^{a}	5.22 ± 0.5^{b}	6.77 ± 0.6^{bc}
Pods (number)	22.12 ± 0.6^{a}	37.22 ± 0.2^{b}	48.22 ± 0.4^{bc}	64.77 ± 0.9^{d}
Root (weight, g)	43.33 ± 0.8^{a}	71.73 ± 0.5^{b}	99.85 ± 0.9^{c}	61.77 ± 0.5^{bd}
Root length (cm)	15.22 ± 0.1^{a}	19.33 ± 0.2^{a}	26.33 ± 0.9^{b}	32.67 ± 0.7^{bc}
Root nodule (number)	7.12±0.3a	10.14 ± 0.3^{a}	16.55 ± 0.6^{b}	36.55 ± 0.7^{c}
Dry matter (g)	86.09 ± 0.4^{a}	129.98 ± 0.7^{b}	160.19 ± 0.5^{c}	137.12 ± 0.4^{bd}

The values are mean ± standard error of four replicates (n=4). The different letters within a row indicate statistical differences at $p<0.05$. Leaf and root weights are oven-dry weights.

The trend in root production was similar to the plant population, with more roots produced in the soil with the higher amendment rates, the increase being nearly 65–100%. The longer the roots, the more root nodules there were, and they were directly influenced by the greater availability of nutrients and improved soil conditions in the soil amended by higher SPS rates. In most soils, legume production is affected by soil biological, physical, and chemical properties, some of which were considered in this study are shown in the data tables. Soil nutrients, moisture, aeration, pH, nodule development (rhizobial symbiosis), and metal toxicity are known parameters that affect legume productivity (biomass production). The data showed that the general soil conditions (Table 4), nutrient status, and metal (Table 5) stresses directly affected the cowpea biomass production. There was a great improvement in the general soil conditions with moisture level ranging from 77–93%, pH was within normal range, and the total soil porosity was between 40–44 % (Table 4), and these reflected on the biomass production (Table 5).

Metal toxicity is an issue for the growth of plant roots, and a certain concentration of metals was available in the soil (Table 3). Despite that, the cowpea plants produced an increasing root biomass in the soils metal concentrations were high (Table 5). The mechanism for this seems to be the high level of cowpea's tolerance to environmental stresses (Langyintuo et al., 2003; Guerra et al., 2017) as pointed out previously. Metals such as Fe are used by legumes for nodule formation and development. The higher availability of Fe measured contributed to the increasing number of nodules with an increase in the rate of SPS (Brear et al., 2013). Araújo et al. (2007) studied the effects of composted textile sludge on growth, nodulation, and nitrogen fixation. The study showed no negative effects on nodule number and weight of the cowpea plants. Miranda et al. (2014) studied the effects of tannery sludge after five years of application on growth and nodulation of cowpea and reported that growth, nodulation, N accumulation, and yield increased by the highest amendment rates, similar to our results. Nodulation is an indicator of biological nitrogen fixation, and the increasing number of nodules recorded (Table 5) indicated that the presence of high concentrations of metals at the high amendment rates had minimal effects on the activities of rhizobia, similar to the findings of Santos et al. (2011). The concentrations of metals measured in cowpea biomass exceeded the standard permissible levels for legumes. However, since the soil originated from a residential area, many metal concentrations remained within permissible limits.

Conclusions

Disposal of SPS into the environment presents a significant concern in PNG. The potential for agricultural use as a management strategy was evaluated by cultivating cowpea. Changes in soil chemistry resulting from SPS amendment, along with plant biomass production and tissue accumulation of metals, were assessed in relation to soil health, agricultural productivity, and risks to livestock and human health. SPS amendment improved all measured parameters, including primary and secondary macronutrients and micronutrients. In most cases, soil and tissue metal concentrations, were dependent on the amendment rate, with the highest concentrations observed at 10 t ha^{-1}. Biomass production on a dry-matter basis also varied with amendment rate, with yields of 0.39, 0.58, 0.72, and 0.62 g m^{-2}. Although concerns remain regarding the presence of metals such as Cd, Ni, and Pb in soil and

Cr, Cu, and Pb in biomass, an amendment rate of 5.0 t ha^{-1} appears optimal for increasing cowpea production while minimizing environmental pollution. These findings suggest that long-term environmental impacts of SPS application would be minimized if the 5.0 t ha^{-1} rate is adopted.

Acknowledgments

The study was supported by funding from the PNG University of Technology and the Eastern Highland Provincial Administration. The authors are grateful to colleagues and fellow students who have contributed directly or indirectly to the study.

Conflict of interest

The authors declare that there are no competing financial or personal interests that may appear to influence the work reported in this paper.

Data availability statement

All the data are included in the manuscript.

Author's contributions

Conceptualization, Methodology, Supervision, and Writing draft and editing: PM; Formal analysis, Data collection, analysis and investigation: LK. All authors read and approved the final draft.

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Growth and Mechanical Stability of *Populus* spp. Plantations on Alluvial Soils with Applied Agroforestry Practices in the Region of Vidin

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Received: 28 April 2026 *Accepted: 21 June 2026*

Abstract

A comparative analysis was conducted on the growth and mechanical stability of *Populus* spp. plantations along the Danube River basin on alluvial soils with a 4x4 m planting scheme and varying ages with applied agroforestry practices. The main soil characteristics have been determined – pH, carbon (C) and nitrogen (N) stock, C/N ratio, and humus content. The growth and productivity of poplar plantations have been assessed through the main dendrometric characteristics – average diameter, average height, stock and mechanical stability coefficient. The plantations show good growth and a low degree of mechanical stability. Of particular economic importance is the cultivation of fast-growing tree species to maximise timber yield in a short period. The initial 4x4 m scheme is suitable for establishment of poplar plantations on alluvial soils, poorly stocked with carbon and nitrogen. Carrying out thinning operations in the poplar plantations around the 5th-6th year after planting would improve the structure, dendrometric characteristics, productivity, and overall strengthening of the stand.

Keywords: *Populus* spp., agroforestry systems, growth, mechanical resilience

Introduction

Agroforestry is a multifunctional, environmentally safe, and modern system of land use. Agroforestry practices are particularly useful for improving the composition of organic matter in the soil – the amount of carbon associated with the resistant fraction increases, while the amount of "aggressive" fulvic acids decreases (Kachova, Ferezliev, 2020).

The establishment of agroforestry systems with the cultivation of tree species along the Danube River shows good results in terms of increasing their productivity and improving soil qualities. Planting agricultural crops, such as corn, melons, and others, among poplars is a good method for increasing their dendrometric characteristics, such as average diameter, average height, and volume. Obtained results provide a reason for agroforestry systems involving *Populus* sp. to be recommended as suitable for establishment along the Danube

River (Kachova, Ferezliev, 2026).

To optimise the productivity of plantations created under specific soil and climatic conditions, it is necessary to understand the development dynamics of these plantations and the changes that occur following the implementation of forestry measures, including when establishing agroforestry systems within them. In the forestry sector of Bulgaria, growing poplar plantations using agroforestry methods has long been a common practice, especially along the Danube River. Young poplar plantations have been co-cultivated with corn, melons, and other agricultural crops, and success has been achieved in improving their growth (Fakirov, 1972; Yakimov et al., 2003; Marinov et al., 2003; Vasev, 2013).

One of the most reliable criteria for assessing the stability of plantations against windthrow, snow breakage, and other mechanical damages to tree stems and crowns, is the mechanical stability coefficient (thinness) (Nykänen et al., 1997; Peltola et al., 1999; Petty, Worrell, 1981; Zhu et al., 2006).

The coefficient of mechanical stability has been tracked by height groups in a study of stands with the edificator Moesian beech (*Fagus moesiaca* (Maly) Czecz.) on the Shumen Plateau (Tsakov et al., 2013). The values of this coefficient are decisive in selecting origins for planting Douglas fir and when conducting thinnings, as the species often suffers from snow and wind breakage (Popov, 2011). This coefficient has been determined in choosing optimal regimes for the establishment and management of Austrian black pine plantations to achieve the maximum total timber utilisation at short rotation and to maintain reliable stability of the stand throughout the entire rotation period (Stankova, 2010). The mechanical stability of plantations from selected *Robinia pseudoacacia* L. clones at ages 5, 7, and 20 has been studied, as well as of plantations on degraded terrains (Dimitrova, 2005; 2019, 2025).

The aim of the present study is to conduct a comparative analysis of the growth and mechanical stability of poplar plantations on alluvial soils with agroforestry practices.

Material and Methods

The objects of study are three poplar plantations established along the Danube River with applied agroforestry practices, following a 4x4 m planting scheme. All sample plots (SP) are located in Natura 2000 and are in the protective riparian zone of the Danube River, where SP1 and SP3 are situated in the territory of the village of Slanotrun, and SP2 in the territory of the town of Vidin.

The soils in the region are alluvial (Alluvial Fluvisol), developed on loess, deep, fresh, sandy, with a groundwater level up to 2 m. Total carbon was determined by the Turin method and total nitrogen by the Kjeldahl method (Donov et al., 1974). Soil samples were taken in three replicates for each sample plot at a depth of 0-20 cm. An average sample was formed for laboratory analyses.

In connection with the study on 9-year-old poplar plantations, sample plots of 2.0 dka in size were established in 2024. Sample plot 2 was established in 2018 with the same size and is used to compare growth and mechanical stability at an older age of over 15 years (table 1).

The heights of the trees in each sample plot were measured with a Vertex IV heightmeter with an accuracy of up to 10 cm. The average height of the stand was calculated using formula (1) of Lorey's (1878):

(1) $H = h1g1 + h2g2 + \ldots + hngn / g1 + g2 + \ldots + gn$ (m), where

h – is a height of each tree (1,2, ….n) (m)
g – is a basal area of each tree (1,2, ….n) (m^2)

Table 1. *Description of the sample plots*

Sample plot	Poplar clone	Age years	Activities	Altitude m	Exposition
SPSP 1	Agathe F	9	2nd and 3rd year with corn	30	east
SP 2	BL	15	2nd year with corn 3rd year with watermelons	30	northwest
SP 3	Agathe F	9	3rd year with corn	40	east

Complete measuring of all stems in the sample plots has been carried out. The diameter of breast height of each stem ($D_{1.30}$) was determined by measuring two perpendicular diameters at a height of 1.30 m with an accuracy of 1 cm, and the average diameter (Dav) of the experimental plot was calculated using the formula (2):

(2) $D_{av}=\sqrt{1.274*G_{av}}$, where

D_{av} – average diameter (cm)
$G_{av}= G_{total}/N$ – average basal area (m^2)
G_{total} – total basal area (m^2)
N – total number of trees

The stem volumes of the poplar trees and the stock of the sample plots in the tables are calculated according to formula (3), derived based on the table of species heights (Krăstanov, 1983).

(3) $V = (0.32h + 1.74)dbh^2 \times \pi/40000$, where

V – volume of tree (m^3)
h – height of tree (m)
dbh – diameter of breast height 1,30 m (cm)

The coefficient of mechanical stability is calculated as ratio ($H/D_{1.30}$) height/diameter of breast height (Schütz, 1999).

The Shapiro-Wilk test has been used to check the normality of the distribution of trees by thickness (Snedecor, Cochran, 1989)л For statistical comparison of mean values between two separate groups, the Student's t-test was used (Kalpić et al., 2011).

Results and Discussion

To meet the growing demand for construction timber, selecting suitable large-diameter poplar clones and optimising spacing are essential for increasing plantation productivity. Soil quality is of crucial importance for the development of seedlings. There are studies that confirm the existence of a direct correlation between the height of woody plants and soil conditions (Duhovnikov et al., 1975).

Table 2 presents the main characteristics of the soils in sample plots: pH, C/N ratio, and the stocks of C and N – recalculated in t/ha in 1 cm of soil with an average bulk density taken as 1.5 g/cm³.

Table 2. *Characteristics of the soils*

Sample plot	pH	Stock of C t/ha	Stock of N t/ha	C/N	Humus %
SP1	6.1	3.46	0.12	27	4.2
SP2	5.8	2.01	0.10	21	2.4
SP3	6.5	2.64	0.11	23	3.3

Soils from the studied sample plots fall within the range of slightly acidic (pH = 5.8 - 6.5). The calculated reserves of carbon and nitrogen indicate that the soils are poorly stocked. The organic matter content is low. Only the soils from SP1 are moderately stocked with organic matter. However, concerning the soil's nitrogen reserves, everywhere it is very low – below 1 t/ha. High summer temperatures and low rainfall during the summer in the area are one of the reasons for the low levels of humus and nitrogen and the active mineralisation of plant residues in the soils along the Danube River (Kirilov et al., 2015). The C/N ratio in the soils, which is an indicator of the rate at which the mineralisation of organic matter occurs, also has low to medium values.

Table 3 presents the summarised dendrometric characteristics of trees in the sample plots of poplar plantations, included in agroforestry systems at the age of 9 (SP1 and SP3) and 15 (SP2) years.

The number of trees per hectare varies from 582 for SP1 to 609 for SP2. The survival rate of individuals in the plantations is over 90%. During the study period, the percentage of fallen individuals varies from 2.6% in SP2 to 6.9% in SP1.

The plantation in SP1 shows better height growth compared to that in SP3, with no difference in diameter growth at the same age. A statistically significant difference was found between the average height of the individuals (t_{exp}=5.560, df=255, and Sig=0.001), and no difference was observed between the average diameter values (t_{exp}=3.088, df=255, and Sig=0.080) in SP1 and SP3. Regarding the dendrobiometrical characteristics, SP2 showed an increase of 19.30 m (250.3%) in average height and 15.4 cm (177.0%) in average diameter

compared to the previous measurement in 2018 (Kachova, Ferezliev, 2026). At the age of 15, the plantation is characterised by relatively good growth and a high stock of 298 m³/ha with an initial growing space of 16 m², without any silvicultural interventions and only about 3% of trees lost.

The comparison of 9-year-old stands by total stock shows that the average annual volume increment is approximately the same, from 7.9 m³/ha for SP1 to 8.4 m³/ha for SP3. The total stock is higher in SP3, which is due to the greater number of trees around the central diameter class 16 (94.6%) and the higher percentage of trees in diameter class 18, which is 5.3% higher than that in SP1.

Table 3. *Dendrometric characteristics of the poplar trees in the sample plots*

Sample plot	*Populus* clone	Diameter (cm)			Height (m)			Basal area (m^2)		Density No/ha	Volume (m^3/ha)
		Dmin	Dmax	Dav	Hmin	Hmax	Hav	Gtotal	Gav		
1	Agathe F	12.3	16.8	15.2	11.0	20.0	16.0	2.1774	0.0181	582	67.889
2	BL	17.4	28.7	24.5	16.0	37.0	27.0	6.3410	0.0473	609	298.998
3	Agathe F	11.3	18.7	15.3	9.0	20.0	15.3	2.3694	0.0184	586	71.431

Dav – average diameter, Dmin – minimum and Dmax – maximum tree diameter;
Hav – average height, Hmin – minimum and Hmax – maximum tree height

A distribution of the trees by absolute diameter classes in 2 cm intervals has been carried out. In SP1, poplars are concentrated in four degrees of thickness: 12 (6 trees - 4.7%), 14 (57 trees – 44.5%), 16 (61 trees – 47.7%), and 18 (4 trees – 3.1%). In SP3, the available number of trees (129) is distributed in the following degrees of thickness: 12 (7 trees - 5.4%), 14 (45 trees – 35%), 16 (64 trees – 49.6%), and 18 (13 trees – 10.7%). In 2024, greater differentiation of the trees in SP2 was observed compared to 2018, across 5 degrees as follows: 18 (3 trees - 2.2%), 22 (7 trees - 5.2%), 24 (94 trees - 70.1%), 26 (22 trees - 16.4%) and 28 (8 trees - 6.1%) (Kachova, Ferezliev, 2026). The indicators from the Shapiro-Wilk test (with significance threshold levels $p>0.05$) show that the distribution of diameters in all sample plots differs statistically significantly from normal ($p<0.001$) (Table 4).

Table 4. *Percentage distribution of the number of trees from Populus spp. plantations by thickness degrees and normality of the distribution*

Sample plot	Thickness degrees (cm)									Number of trees	Shapiro-Wilk test W	Significance level P
	12	14	16	18	20	22	24	26	28			
	Number of trees (%)											
SP1	4.7	44.5	47.7	3.1						128	0.712	0.000
SP2				2.2		5.2	70.1	16.4	6.1	134	0.704	0.000
SP3	5.4	35	49.6	10.7						129	0.803	0.000

The results confirm the conclusion of a previous study that in poplar plantations, when applying agroforestry practices, regardless of age, higher values of the main dendrobiometrical indicators are recorded in the early stages of growth. Over the years, these

differences diminish (Kachova, Ferezliev, 2020). A probable reason for this is the increased intraspecific competition among the trees, especially regarding the crown, which overrides the initial effect of improved growth conditions (Zhang et al., 2022).

The study shows significant influence of all tending practices on the growth and productivity of poplar plantations. Studies on 12 clones of *Populus* x *euroamericana* at four densities over a 14-year rotation period indicate that to achieve a diameter of 24 to 35 cm, a growing space of 10 to 32 m² is required, with the optimal period for the first thinning being in the 4th to 5th year (Liu et al., 2025).

In dense plantations, the final timber yield is often lower than the intermediate yields, The first studies on the beginning and intensity of thinning cuts in poplar plantations of *Populus* x *euroamericana* (Dode) Guinier cv. *regenerata* along the Danube River were conducted by Naydenova and Tsvetkov (1964) and Fakirov (1968). The results indicate that in 5-10-year-old dense plantations, both moderate and intensive thinnings can be carried out depending on the objective. As the age increases and thinning is delayed, more intensive thinning is applied, primarily in medium and small assortments (Fakirov, 1968; Giordano and Avanzo, 1973).

It has been established that plantations of *Populus regenerata* on alluvial-meadow soils along the Danube River with a density of 3x3 m have the highest productivity per hectare, ranging from 425 to 461 m³/ha at the age of 14-16. With the initial planting scheme of 4x4 m, at the same age this productivity is from 304 to 326 m³/ha (Naydenova, Tsvetkov, 1964). Depending on the poplar clone, at a density of 4x4 m, the average volume increment reaches 11-15 m³/ha. Therefore, to increase productivity and produce large timber in a short period, it is recommended to establish less dense plantations. From an economic point of view and for convenience in mechanised soil cultivation, the density should not go below 4x4 m (Fakirov, 1972).

In terms of the number of thinnings, among three thinnings at a 4x4 m density, 4-year-old poplar stands show the best growth in height (8.91 m) and diameter (17.8 cm) (Naydenova, Tsvetkov, 1964). The values of 15.2 cm (SP1) and 15.3 cm (SP3) for the average diameter at 9 years of age of the studied poplar stands indicate that carrying out tending practices would improve their dendrometric characteristics and productivity.

The critical factors regarding site conditions, such as climate conditions, topography, elevation, density, and others, can affect the mechanical resilience of the stands.

Figure 1 presents the values of the mechanical stability coefficient (Kmst) for the sample plots of poplars with agroforestry by degrees of thickness (DT). The analysis of the data in the sample plots shows that the stand in sample plot 3 has a better mechanical stability coefficient (1.0), while for the other crops, the average value of this coefficient does not exceed 1.1.

The trees of all thickness grades in SP3 have highest values of the mechanical stability coefficient (≤1.0), which determines the best overall resilience of the stand. In SP1, which is of the same age, and in the older plantation (SP2) with a coefficient of 1.0, the trees are from the lower degrees of thickness. In the higher degrees, around which the average diameter is grouped (DT 16 for SP1 and DT 24 for SP2), the highest number of trees is concentrated (64% for SP1 and 69% for SP2) with a resilience coefficient greater than 1.0, which also determines the lower resilience of the stands, regardless of their age.

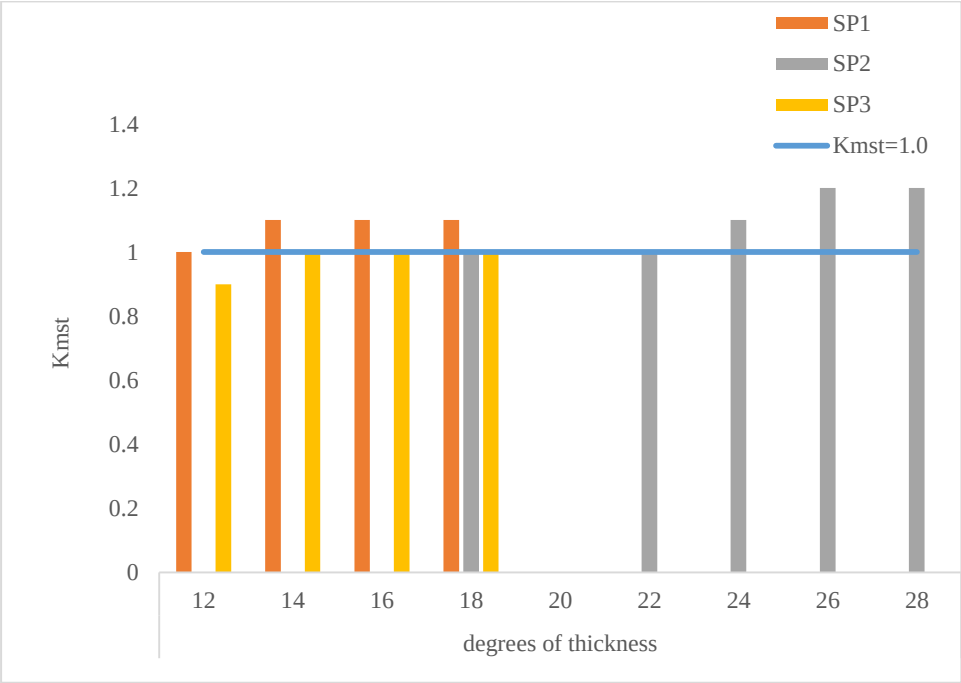

Fig. 1. *Mechanical stability coefficient (Kmst) of poplar trees from the sample plots by degrees of thickness*

The medium degrees of thickness, represented by the largest number of stems, increase the quantity of large and medium assortments in the plantations (Ferezliev et al., 2018). Regarding the assortment structure for SP2 and the control experimental plot (without agroforestry practice), it was found that the application of an agroforestry system does not significantly affect the type (by categories and classes) of the obtained assortments. Based on the age of the main felling and the average dimensions (height and diameter) of the stand, it is then possible, although approximately, to estimate the dimensions of the harvested assortments in the order of class IV–VI for SP2, encompassing small and medium construction timber (Kachova, Ferezliev, 2026).

The stability of forest stands against windthrow, snow breakage, and other mechanical damages to trees also depends on the tree crown and the density of the stands (Nykänen et al., 1997; Peltola et al., 1999; Petty, Worrell, 1981). The size of the crowns and the arrangement of branches are largely species-specific (Nykänen et al., 1997). The percentage ratio of the crown to the tree height (the so-called crown index) is crucial for the tree and is closely related to its productivity and stability.

Most vulnerable to mechanical damages are trees of smaller diameter classes, regardless of the tree species. Suppressed trees from the lower part of the stand in black locust plantations on degraded lands are characterised by small crowns, increased height growth due to light deficiency, and reduced vitality, which also determines their greater instability (Tsakov, Dimitrova, 2003).

This was also observed in a study of the dynamics of the values of the mechanical stability coefficient by height groups of stands with an edificator Moesian beech (*Fagus moesiaca* (Maly) Czecz.) (Tsakov et al., 2013).

The stems of 7- and 20-year-old black locust plantations from selected *Robinia pseudoacacia* L. clones, grown with an initial growing space of 4.5 m², exhibit a low degree of mechanical stability, confirmed by the $H/D_{1.30}$ ratio. In case a good stock of 200 to 242 m³/ha of wood with impaired stand stability is achieved at lower density, it is recommended to carry out tending measures in the black locust plantations, which would improve dendrobiometric characteristics and the overall strengthening of the stands (Dimitrova, 2019; Dimitrova, 2025).

The data on the influence of density on the stability of stands are highly contradictory (Schütz, 1999; Nykänen et al., 1997; Peltola et al., 1999; Zhu et al., 2006). According to Nykänen et al. (1997), denser stands are less stable because high density promotes the development of thinner stems with asymmetrical and short crowns.

Zhu et al. (2006), in turn, found that with increasing density, the overall size of the main types of mechanical damages (uprooting, breakage, bending, crown disruption) caused by snow and wind in the plantations of various tree species they studied decreases. The authors explain the results by the fact that sparser plantations generally retain less snow, but the amount of snow on individual stems, in turn, is greater, i.e., the exerted pressure is higher.

The damage by a storm was studied on three-year-old plantations of four poplar clones at three densities. It was found that at the closest distance, where crown shaking would be minimised, the trees that were not uprooted had a larger cross-sectional root area in the direction of the wind compared to the uprooted trees. At the greatest distance, where crown shaking would be maximal, the resilient trees had a larger cross-sectional root area not only on the windward side but also on the opposite side. Furthermore, the most susceptible poplar clone had the highest aboveground biomass per unit area of root cross-section (Constance et al., 1996).

When determining the optimal regimes for the sustainable management of poplar plantations with a short rotation, those with good dendrometric characteristics, high productivity, and a coefficient of mechanical stability not exceeding 1.0 are preferred. The initial 4x4 m scheme is suitable for creating poplar plantations along the Danube River. In case a good stock of 298 m^3/ha at the age of 15 is achieved with an initial growth space of 16 m^2, carrying out moderate thinning operations in the poplar plantations around the 5th-6th year after planting would improve the structure, dendrometric characteristics, productivity, and overall strengthening of the stand.

Conclusion

The stands in 9- and 15-year-old plantations of selected *Populus* spp. clones, grown on alluvial soils with agroforestry practices, possess good growth and a low degree of mechanical stability, confirmed by the $H/D_{1.30}$ ratio.

Of particular economic importance is the cultivation of fast-growing tree species to achieve maximum timber yield in a short period. The initial 4x4 m scheme is suitable for creating poplar plantations on alluvial soils, poorly stocked with carbon and nitrogen. Carrying out moderate thinning operations in the poplar plantations around the 5th-6th year after planting would improve the structure, dendrometric characteristics, productivity, and overall strengthening of the stand.

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